Design-by-Contract (DbC)

Readings: OOSC2 Chapter 11

YORK UNIVERSITÉ UNIVERSITY

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CHEN-WEI WANG

Motivation: Catching Defects – Design or Implementation Phase?

- To minimize *development costs*, minimize *software defects*.

  ∵ The cost of fixing defects *increases exponentially* as software progresses through the development lifecycle:

  Requirements → *Design* → *Implementation* → Release

  ∴ Catch defects *as early as possible*.

Design and architecture	Implementation	Integration testing	Customer beta test	Postproduct release
1X*	5X	10X	15X	30X

- Discovering *defects* after **release** costs up to 30 times more than catching them in the **design** phase.
- Choice of *design language* for your project is therefore of paramount importance.

Source: Minimizing code defects to improve software quality and lower development costs.

What This Course Is About

- Focus is *design*
  - ***Architecture***: (many) ***inter-related*** modules
  - ***Specification***: ***precise*** (functional) interface of each module
- For this course, having a prototypical, *working* implementation for your design suffices.
- A later *refinement* into more efficient data structures and algorithms is beyond the scope of this course.

  [assumed from EECS2011, EECS3101]

∴ Having a suitable language for **design** matters the most.

Q: Is Java also a "good" **design** language?

A: Let's first understand what a "good" **design** is.

Terminology: Contract, Client, Supplier

- A *supplier* implements/provides a service (e.g., microwave).
- A *client* uses a service provided by some supplier.
  - The client are required to follow certain instructions to obtain the service (e.g., supplier **assumes** that client powers on, closes door, and heats something that is not explosive).
  - If instructions are followed, the client would **expect** that the service does what is guaranteed (e.g., a lunch box is heated).
  - The client does not care how the supplier implements it.
- What then are the *benefits* and *obligations* os the two parties?

	benefits	*obligations*
CLIENT	obtain a service	follow instructions
SUPPLIER	assume instructions followed	provide a service

- There is a *contract* between two parties, violated if:
  - The instructions are not followed. [Client's fault]
  - Instructions followed, but service not satisfactory. [Supplier's fault]

Client, Supplier, Contract in OOP (1)

```
class Microwave {
  private boolean on;
  private boolean locked;
  void power() {on = true;}
  void lock() {locked = true;}
  void heat(Object stuff) {
    /* Assume: on && locked */
    /* stuff not explosive. */
} }
```

```
class MicrowaveUser {
  public static void main(...) {
    Microwave m = new Microwave();
    Object obj = ???;
    m.power(); m.lock();]
    m.heat(obj);
} }
```

Method call **m.heat(obj)** indicates a client-supplier relation.

- **Client**: resident class of the method call [`MicrowaveUser`]
- **Supplier**: type of context object (or call target) **m** [`Microwave`]

Client, Supplier, Contract in OOP (2)

```
class Microwave {
  private boolean on;
  private boolean locked;
  void power() {on = true;}
  void lock() {locked = true;}
  void heat(Object stuff) {
    /* Assume: on && locked */
    /* stuff not explosive. */ }}
```

```
class MicrowaveUser {
  public static void main(...) {
    Microwave m = new Microwave();
    Object obj = ???;
    m.power(); m.lock();
    m.heat(obj);
}} }
```

- The *contract* is *honoured* if:
  - Right **before** the method call :
    - State of `m` is as assumed: `m.on==true` and `m.locked==ture`
    - The input argument `obj` is valid (i.e., not explosive).
  - Right **after** the method call : `obj` is properly heated.
- If any of these fails, there is a *contract violation*.
  - `m.on` or `m.locked` is `false` ⇒ `MicrowaveUser`'s fault.
  - `obj` is an explosive ⇒ `MicrowaveUser`'s fault.
  - A fault from the client is identified ⇒ Method call will not start.
  - Method executed but `obj` not properly heated ⇒ `Microwave`'s fault

What is a Good Design?

- A "good" design should *explicitly* and *unambiguously* describe the *contract* between **clients** (e.g., users of Java classes) and **suppliers** (e.g., developers of Java classes). We such a contractual relation a *specification* .
- When you conduct *software design*, you should be guided by the "appropriate" contracts between users and developers.
  - Instructions to **clients** should *not be unreasonable*.
    e.g., asking them to assemble internal parts of a microwave
  - Working conditions for **suppliers** should *not be unconditional*.
    e.g., expecting them to produce a microwave which can safely heat an explosive with its door open!
  - You as a designer should strike proper balance between **obligations** and **benefits** of clients and suppliers.
    e.g., What is the obligation of a binary-search user (also benefit of a binary-search implementer)? [The input array is sorted.]
  - Upon contract violation, there should be the fault of **only one side**.
  - This design process is called *Design by Contract (DbC)* .

A Simple Problem: Bank Accounts

Provide an object-oriented solution to the following problem:

REQ1 : Each account is associated with the *name* of its owner (e.g., `"Jim"`) and an integer *balance* that is always positive.

REQ2 : We may *withdraw* an integer amount from an account.

REQ3 : Each bank stores a list of *accounts*.

REQ4 : Given a bank, we may *add* a new account in it.

REQ5 : Given a bank, we may *query* about the associated account of a owner (e.g., the account of `"Jim"`).

REQ6 : Given a bank, we may *withdraw* from a specific account, identified by its name, for an integer amount.

Let's first try to work on **REQ1** and **REQ2** in Java.
This may not be as easy as you might think!

Playing the Various Versions in Java

- **Download** the project archive (a zip file) here:
  `http://www.eecs.yorku.ca/~jackie/teaching/lectures/2019/W/EECS3311/codes/DbCIntro.zip`
- Follow this tutorial to learn how to **import** an project archive into your workspace in Eclipse:
  `https://youtu.be/h-rgdQZg2qY`
- Follow this tutorial to learn how to **enable** assertions in Eclipse:
  `https://youtu.be/OEgRV4a5Dzg`

Version 1: An Account Class

```java
public class AccountV1 {
      private String owner;
      private int balance;
      public String getOwner() { return owner; }
      public int getBalance() { return balance; }
      public AccountV1(String owner, int balance) {
            this.owner = owner; this.balance = balance;
      }
      public void withdraw(int amount) {
            this.balance = this.balance - amount;
      }
      public String toString() {
            return owner + "'s current balance is: " + balance;
      }
}
```

- Is this a good design? Recall **REQ1**: Each account is associated with ... an integer balance that is *always positive*.
- This requirement is *not* reflected in the above Java code.

Version 1: Why Not a Good Design? (1)

```java
public class BankAppV1 {
  public static void main(String[] args) {
    System.out.println("Create an account for Alan with balance -10:");
    AccountV1 alan = new AccountV1("Alan", -10);
    System.out.println(alan);
```

Console Output:

```
Create an account for Alan with balance -10:
Alan's current balance is: -10
```

- Executing `AccountV1`'s constructor results in an account object whose *state* (i.e., values of attributes) is *invalid* (i.e., Alan's balance is negative). ⇒ Violation of **REQ1**
- Unfortunately, both client and supplier are to be blamed: `BankAppV1` passed an invalid balance, but the API of `AccountV1` does not require that! ⇒ A lack of defined contract

Version 1: Why Not a Good Design? (2)

```java
public class BankAppV1 {
  public static void main(String[] args) {
    System.out.println("Create an account for Mark with balance 100:");
    AccountV1 mark = new AccountV1("Mark", 100);
    System.out.println(mark);
    System.out.println("Withdraw -1000000 from Mark's account:");
    mark.withdraw(-1000000);
    System.out.println(mark);
```

```
Create an account for Mark with balance 100:
Mark's current balance is: 100
Withdraw -1000000 from Mark's account:
Mark's current balance is: 1000100
```

- Mark's account state is always valid (i.e., 100 and 1000100).
- Withdraw amount is never negative! ⇒ Violation of **REQ2**
- Again a lack of contract between `BankAppV1` and `AccountV1`.

Version 1: Why Not a Good Design? (3)

```java
public class BankAppV1 {
  public static void main(String[] args) {
    System.out.println("Create an account for Tom with balance 100:");
    AccountV1 tom = new AccountV1("Tom", 100);
    System.out.println(tom);
    System.out.println("Withdraw 150 from Tom's account:");
    tom.withdraw(150);
    System.out.println(tom);
```

```
Create an account for Tom with balance 100:
Tom's current balance is: 100
Withdraw 150 from Tom's account:
Tom's current balance is: -50
```

- Withdrawal was done via an "appropriate" reduction, but the resulting balance of Tom is *invalid*. ⇒ Violation of **REQ1**
- Again a lack of contract between `BankAppV1` and `AccountV1`.

Version 1: How Should We Improve it? (1)

Preconditions of a method specify the precise circumstances under which that method can be executed.

- Precond. of `divide(int x, int y)`? [`y != 0`]
- Precond. of `binSearch(int x, int[] xs)`? [`xs` is sorted]
- Precond. of `topoSort(Graph g)`? [`g` is a DAG]

Version 1: How Should We Improve it? (2)

- The best we can do in Java is to encode the *logical negations* of preconditions as *exceptions*:
  - `divide(int x, int y)` throws `DivisionByZeroException` when `y == 0`.
  - `binSearch(int x, int[] xs)` throws `ArrayNotSortedException` when `xs` is *not* sorted.
  - `topoSort(Graph g)` throws `NotDAGException` when `g` is *not* directed and acyclic.
  - Design your method by specifying the *preconditions* (i.e., ***service*** conditions for *valid* inputs) it requires, not the *exceptions* (i.e., ***error*** conditions for *invalid* inputs) for it to fail.
- Create Version 2 by adding *exceptional conditions* (an *approximation* of *preconditions*) to the constructor and `withdraw` method of the `Account` class.

Version 2: Added Exceptions to Approximate Method Preconditions

```java
public class AccountV2 {
  public AccountV2(String owner, int balance) throws
      BalanceNegativeException
  {
    if( balance < 0 ) { /* negated precondition */
      throw new BalanceNegativeException(); }
    else { this.owner = owner; this.balance = balance; }
  }
  public void withdraw(int amount) throws
      WithdrawAmountNegativeException, WithdrawAmountTooLargeException {
    if( amount < 0 ) { /* negated precondition */
      throw new WithdrawAmountNegativeException(); }
    else if ( balance < amount ) { /* negated precondition */
      throw new WithdrawAmountTooLargeException(); }
    else { this.balance = this.balance - amount; }
  }
```

Version 2: Why Better than Version 1? (1)

```
1  public class BankAppV2 {
2   public static void main(String[] args) {
3    System.out.println("Create an account for Alan with balance -10:");
4    try {
5     AccountV2 alan = new AccountV2("Alan", -10);
6     System.out.println(alan);
7    }
8    catch (BalanceNegativeException bne) {
9     System.out.println("Illegal negative account balance.");
10   }
```

```
Create an account for Alan with balance -10:
Illegal negative account balance.
```

L6: When attempting to call the constructor `AccountV2` with a negative balance `-10`, a `BalanceNegativeException` (i.e., *precondition* violation) occurs, *preventing further operations upon this invalid object*.

Version 2: Why Better than Version 1? (2.1)

```
public class BankAppV2 {
 public static void main(String[] args) {
  System.out.println("Create an account for Mark with balance 100:");
  try {
   AccountV2 mark = new AccountV2("Mark", 100);
   System.out.println(mark);
   System.out.println("Withdraw -1000000 from Mark's account:");
   mark.withdraw(-1000000);
   System.out.println(mark);
  }
  catch (BalanceNegativeException bne) {
   System.out.println("Illegal negative account balance.");
  }
  catch (WithdrawAmountNegativeException wane) {
   System.out.println("Illegal negative withdraw amount.");
  }
  catch (WithdrawAmountTooLargeException wane) {
   System.out.println("Illegal too large withdraw amount.");
  }
```


Version 2: Why Better than Version 1? (2.2)

Console Output:

```
Create an account for Mark with balance 100:
Mark's current balance is: 100
Withdraw -1000000 from Mark's account:
Illegal negative withdraw amount.
```

- **L9**: When attempting to call method `withdraw` with a positive but too large amount `150`, a `WithdrawAmountTooLargeException` (i.e., *precondition* violation) occurs, *preventing the withdrawal from proceeding*.
- We should observe that *adding preconditions* to the supplier `BankV2`'s code forces the client `BankAppV2`'s code to *get complicated by the `try-catch` statements*.
- Adding clear contract (*preconditions* in this case) to the design ***should not*** be at the cost of complicating the client's code!!

Version 2: Why Better than Version 1? (3.1)

```
1  public class BankAppV2 {
2   public static void main(String[] args) {
3    System.out.println("Create an account for Tom with balance 100:");
4    try {
5     AccountV2 tom = new AccountV2("Tom", 100);
6     System.out.println(tom);
7     System.out.println("Withdraw 150 from Tom's account:");
8     tom.withdraw(150);
9     System.out.println(tom);
10   }
11   catch (BalanceNegativeException bne) {
12    System.out.println("Illegal negative account balance.");
13   }
14   catch (WithdrawAmountNegativeException wane) {
15    System.out.println("Illegal negative withdraw amount.");
16   }
17   catch (WithdrawAmountTooLargeException wane) {
18    System.out.println("Illegal too large withdraw amount.");
19   }
```

Version 2: Why Better than Version 1? (3.2)

Console Output:

```
Create an account for Tom with balance 100:
Tom's current balance is: 100
Withdraw 150 from Tom's account:
Illegal too large withdraw amount.
```

- **L9**: When attempting to call method `withdraw` with a negative amount `-1000000`, a `WithdrawAmountNegativeException` (i.e., *precondition* violation) occurs, *preventing the withdrawal from proceeding*.
- We should observe that due to the *added preconditions* to the supplier `BankV2`'s code, the client `BankAppV2`'s code is forced to *repeat the long list of the `try-catch` statements*.
- Indeed, adding clear contract (*preconditions* in this case) ***should not*** be at the cost of complicating the client's code!!

Version 2: Why Still Not a Good Design? (1)

```
1  public class AccountV2 {
2    public AccountV2(String owner, int balance) throws
3        BalanceNegativeException
4    {
5      if( balance < 0 ) { /* negated precondition */
6        throw new BalanceNegativeException(); }
7      else { this.owner = owner; this.balance = balance; }
8    }
9    public void withdraw(int amount) throws
10       WithdrawAmountNegativeException, WithdrawAmountTooLargeException {
11     if( amount < 0 ) { /* negated precondition */
12       throw new WithdrawAmountNegativeException(); }
13     else if ( balance < amount ) { /* negated precondition */
14       throw new WithdrawAmountTooLargeException(); }
15     else { this.balance = this.balance - amount; }
16   }
```

- Are all the *exception* conditions ($\neg$ *preconditions*) appropriate?
- What if `amount == balance` when calling `withdraw`?

Version 2: Why Still Not a Good Design? (2.1)

```
1  public class BankAppV2 {
2    public static void main(String[] args) {
3      System.out.println("Create an account for Jim with balance 100:");
4      try {
5        AccountV2 jim = new AccountV2("Jim", 100);
6        System.out.println(jim);
7        System.out.println("Withdraw 100 from Jim's account:");
8        jim.withdraw(100);
9        System.out.println(jim);
10     }
11     catch (BalanceNegativeException bne) {
12       System.out.println("Illegal negative account balance.");
13     }
14     catch (WithdrawAmountNegativeException wane) {
15       System.out.println("Illegal negative withdraw amount.");
16     }
17     catch (WithdrawAmountTooLargeException wane) {
18       System.out.println("Illegal too large withdraw amount.");
19     }
```


Version 2: Why Still Not a Good Design? (2.2)

```
Create an account for Jim with balance 100:
Jim's current balance is: 100
Withdraw 100 from Jim's account:
Jim's current balance is: 0
```

L9: When attempting to call method `withdraw` with an amount `100` (i.e., equal to Jim's current balance) that would result in a **zero** balance (clearly a violation of **REQ1**), there should have been a *precondition* violation.

Supplier `AccountV2`'s *exception* condition `balance < amount` has a *missing case*:

- Calling `withdraw` with `amount == balance` will also result in an invalid account state (i.e., the resulting account balance is **zero**).
- ∴ **L13** of `AccountV2` should be `balance <= amount`.

Version 2: How Should We Improve it?

- **Even without** fixing this insufficient *precondition*, we could have avoided the above scenario by *checking at the end of each method that the resulting account is valid*.

  ⇒ We consider the condition `this.balance > 0` as *invariant* throughout the lifetime of all instances of `Account`.

- *Invariants* of a class specify the precise conditions which all instances/objects of that class must satisfy.
  - Inv. of `CSMajoarStudent`? [`gpa >= 4.5`]
  - Inv. of `BinarySearchTree`? [in-order trav. → sorted key seq.]
- The best we can do in Java is encode invariants as *assertions*:
  - `CSMajorStudent`: **`assert`** `this.gpa >= 4.5`
  - `BinarySearchTree`: **`assert`** `this.inOrder() is sorted`
  - Unlike exceptions, assertions are not in the class/method API.
- Create Version 3 by adding *assertions* to the end of constructor and `withdraw` method of the `Account` class.

Version 3: Added Assertions to Approximate Class Invariants

```
public class AccountV3 {
  public AccountV3(String owner, int balance) throws
    BalanceNegativeException
  {
    if(balance < 0) { /* negated precondition */
      throw new BalanceNegativeException(); }
    else { this.owner = owner; this.balance = balance; }
    assert this.getBalance() > 0 : "Invariant: positive balance";
  }
  public void withdraw(int amount) throws
    WithdrawAmountNegativeException, WithdrawAmountTooLargeException {
    if(amount < 0) { /* negated precondition */
      throw new WithdrawAmountNegativeException(); }
    else if (balance < amount) { /* negated precondition */
      throw new WithdrawAmountTooLargeException(); }
    else { this.balance = this.balance - amount; }
    assert this.getBalance() > 0 : "Invariant: positive balance";
  }
```


Version 3: Why Better than Version 2?

```
1  public class BankAppV3 {
2    public static void main(String[] args) {
3      System.out.println("Create an account for Jim with balance 100:");
4      try { AccountV3 jim = new AccountV3("Jim", 100);
5            System.out.println(jim);
6            System.out.println("Withdraw 100 from Jim's account:");
7            jim. withdraw(100) ;
8            System.out.println(jim); }
9            /* catch statements same as this previous slide:
10            * Version 2: Why Still Not a Good Design? (2.1) */
```

```
Create an account for Jim with balance 100:
Jim's current balance is: 100
Withdraw 100 from Jim's account:
Exception in thread "main"
    java.lang.AssertionError: Invariant: positive balance
```

L8: Upon completion of `jim.withdraw(100)`, Jim has a **zero** balance, an assertion failure (i.e., *invariant* violation) occurs, *preventing further operations on this invalid account object*.

Version 3: Why Still Not a Good Design?

Let's review what we have added to the method `withdraw`:

- From Version 2 : *exceptions* encoding **negated** *preconditions*
- From Version 3 : *assertions* encoding the *class invariants*

```
public class AccountV3 {
  public void withdraw(int amount) throws
    WithdrawAmountNegativeException, WithdrawAmountTooLargeException {
    if( amount < 0 ) { /* negated precondition */
      throw new WithdrawAmountNegativeException(); }
    else if ( balance < amount ) { /* negated precondition */
      throw new WithdrawAmountTooLargeException(); }
    else { this.balance = this.balance - amount; }
    assert this.getBalance() > 0 : "Invariant: positive balance"; }
```

However, there is ***no*** *contract* in `withdraw` which specifies:

- Obligations of supplier (`AccountV3`) if preconditions are met.
- Benefits of client (`BankAppV3`) after meeting preconditions.

  ⇒ We illustrate how problematic this can be by creating Version 4 , where deliberately mistakenly implement `withdraw`.

Version 4: What If the Implementation of `withdraw` is Wrong? (1)

```
1  public class AccountV4 {
2   public void withdraw(int amount) throws
3     WithdrawAmountNegativeException, WithdrawAmountTooLargeException
4   { if(amount < 0) { /* negated precondition */
5      throw new WithdrawAmountNegativeException(); }
6     else if (balance < amount) { /* negated precondition */
7      throw new WithdrawAmountTooLargeException(); }
8     else { /* WRONT IMPLEMENTATION */
9      this.balance = this.balance + amount; }
10    assert this.getBalance() > 0 :
11     owner + "Invariant: positive balance"; }
```

- Apparently the implementation at **L11** is ***wrong***.
- Adding a positive amount to a valid (positive) account balance would not result in an invalid (negative) one.
  ⇒ The **class invariant** will ***not*** catch this flaw.
- When something goes wrong, a good *design* (with an appropriate *contract*) should report it via a *contract violation*.

Version 4: What If the Implementation of `withdraw` is Wrong? (2)

```
1  public class BankAppV4 {
2   public static void main(String[] args) {
3     System.out.println("Create an account for Jeremy with balance 100:");
4     try { AccountV4 jeremy = new AccountV4("Jeremy", 100);
5           System.out.println(jeremy);
6           System.out.println("Withdraw 50 from Jeremy's account:");
7           jeremy.withdraw(50);
8           System.out.println(jeremy); }
9     /* catch statements same as this previous slide:
10     * Version 2: Why Still Not a Good Design? (2.1) */
```

```
Create an account for Jeremy with balance 100:
Jeremy's current balance is: 100
Withdraw 50 from Jeremy's account:
Jeremy's current balance is: 150
```

L7: Resulting balance of Jeremy is valid (150 > 0), but withdrawal was done via an *mistaken* increase. ⇒ Violation of **REQ2**

Version 4: How Should We Improve it?

- *Postconditions* of a method specify the precise conditions which it will satisfy upon its completion.
  This relies on the assumption that right before the method starts, its preconditions are satisfied (i.e., inputs valid) and invariants are satisfied (i.e,. object state valid).
  - Postcondition of `double divide(int x, int y)`?
    [**Result** $\times$ $y == x$]
  - Postcondition of `boolean binSearch(int x, int[] xs)`?
    [$x \in xs \iff$ **Result**]
- The best we can do in Java is, similar to the case of invariants, encode postconditions as *assertions*.
  But again, unlike exceptions, these assertions will not be part of the class/method API.
- Create Version 5 by adding *assertions* to the end of `withdraw` method of the `Account` class.

Version 5: Added Assertions to Approximate Method Postconditions

```
1  public class AccountV5 {
2   public void withdraw(int amount) throws
3      WithdrawAmountNegativeException, WithdrawAmountTooLargeException {
4     int oldBalance = this.balance;
5     if(amount < 0) { /* negated precondition */
6      throw new WithdrawAmountNegativeException(); }
7     else if (balance < amount) { /* negated precondition */
8      throw new WithdrawAmountTooLargeException(); }
9     else { this.balance = this.balance - amount; }
10    assert this.getBalance() > 0 :"Invariant: positive balance";
11    assert this.getBalance() == oldBalance - amount :
12     "Postcondition: balance deducted"; }
```

A postcondition typically relates the pre-execution value and the post-execution value of each relevant attribute (e.g.,`balance` in the case of `withdraw`).
⇒ Extra code (**L4**) to capture the pre-execution value of `balance` for the comparison at **L11**.

Version 5: Why Better than Version 4?

```
1  public class BankAppV5 {
2   public static void main(String[] args) {
3    System.out.println("Create an account for Jeremy with balance 100:");
4    try { AccountV5 jeremy = new AccountV5("Jeremy", 100);
5          System.out.println(jeremy);
6          System.out.println("Withdraw 50 from Jeremy's account:");
7          jeremy.withdraw(50);
8          System.out.println(jeremy); }
9          /* catch statements same as this previous slide:
10          * Version 2: Why Still Not a Good Design? (2.1) */
```

```
Create an account for Jeremy with balance 100:
Jeremy's current balance is: 100
Withdraw 50 from Jeremy's account:
Exception in thread "main"
  java.lang.AssertionError: Postcondition: balance deducted
```

L8: Upon completion of `jeremy.withdraw(50)`, Jeremy has a wrong balance 150, an assertion failure (i.e., *postcondition* violation) occurs, *preventing further operations on this invalid account object*.

Evolving from Version 1 to Version 5

	Improvements Made	Design *Flaws*
V1	–	Complete lack of Contract
V2	Added exceptions as *method preconditions*	Preconditions not strong enough (i.e., with missing cases) may result in an invalid account state.
V3	Added assertions as *class invariants*	Incorrect implementations do not necessarily result in a state that violates the class invariants.
V4	Deliberately changed `withdraw`'s implementation to be **incorrect**.	The incorrect implementation does not result in a state that violates the class invariants.
V5	Added assertions as *method postconditions*	–

- In Versions 2, 3, 4, 5, **preconditions** approximated as *exceptions*.
  ☹ These are ***not preconditions***, but their *logical negation*.
  ☹ Client `BankApp`'s code ***complicated*** by repeating the list of `try-catch` statements.
- In Versions 3, 4, 5, **class invariants** and **postconditions** approximated as *assertions*.
  ☹ Unlike exceptions, these assertions will ***not appear in the API*** of `withdraw`. Potential clients of this method ***cannot know***: **1)** what their benefits are; and **2)** what their suppliers' obligations are.
  ☹ For postconditions, ***extra code*** needed to capture pre-execution values of attributes.

Version 5: Contract between Client and Supplier

	benefits	*obligations*
`BankAppV5.main` (CLIENT)	balance deduction positive balance	amount non-negative amount not too large
`BankV5.withdraw` (SUPPLIER)	amount non-negative amount not too large	balance deduction positive balance

	benefits	*obligations*
CLIENT	postcondition & invariant	precondition
SUPPLIER	precondition	postcondition & invariant

DbC in Java

DbC is possible in Java, but not appropriate for your learning:

- *Preconditions* of a method:
  Supplier
  - Encode their logical negations as exceptions.
  - In the **beginning** of that method, a list of `if`-statements for throwing the appropriate exceptions.

  Client
  - A list of `try-catch`-statements for handling exceptions.
- *Postconditions* of a method:
  Supplier
  - Encoded as a list of assertions, placed at the **end** of that method.

  Client
  - All such assertions do not appear in the API of that method.
- *Invariants* of a class:
  Supplier
  - Encoded as a list of assertions, placed at the **end** of **every** method.

  Client
  - All such assertions do not appear in the API of that class.

DbC in Eiffel: Supplier

DbC is supported natively in Eiffel for **supplier**:

```
class ACCOUNT
create
      make
feature -- Attributes
      owner : STRING
      balance : INTEGER
feature -- Constructors
      make(nn: STRING; nb: INTEGER)
            require -- precondition
                  positive_balance: nb > 0
            do
                  owner := nn
                  balance := nb
            end
feature -- Commands
      withdraw(amount: INTEGER)
            require -- precondition
                  non_negative_amount: amount > 0
                  affordable_amount: amount <= balance -- problematic, why?
            do
                  balance := balance - amount
            ensure -- postcondition
                  balance_deducted: balance = old balance - amount
            end
invariant -- class invariant
      positive_balance: balance > 0
end
```


DbC in Eiffel: Contract View of Supplier

Any potential **client** who is interested in learning about the kind of services provided by a **supplier** can look through the *contract view* (without showing any implementation details):

```
class ACCOUNT
create
      make
feature -- Attributes
      owner : STRING
      balance : INTEGER
feature -- Constructors
      make(nn: STRING; nb: INTEGER)
            require -- precondition
                  positive_balance: nb > 0
            end
feature -- Commands
      withdraw(amount: INTEGER)
            require -- precondition
                  non_negative_amount: amount > 0
                  affordable_amount: amount <= balance -- problematic, why?
            ensure -- postcondition
                  balance_deducted: balance = old balance - amount
            end
invariant -- class invariant
      positive_balance: balance > 0
end
```


DbC in Eiffel: Anatomy of a Class

```
class SOME_CLASS
create
  -- Explicitly list here commands used as constructors
feature -- Attributes
  -- Declare attribute here
feature -- Commands
  -- Declare commands (mutators) here
feature -- Queries
  -- Declare queries (accessors) here
invariant
  -- List of tagged boolean expressions for class invariants
end
```

- Use `feature` clauses to group attributes, commands, queries.
- Explicitly declare list of commands under `create` clause, so that they can be used as class constructors.
  [See the `groups` panel in Eiffel Studio.]
- The *class invariant* `invariant` clause may be omitted:
  - There's no class invariant: any resulting object state is acceptable.
  - The class invariant is equivalent to writing **`invariant`** ***true***

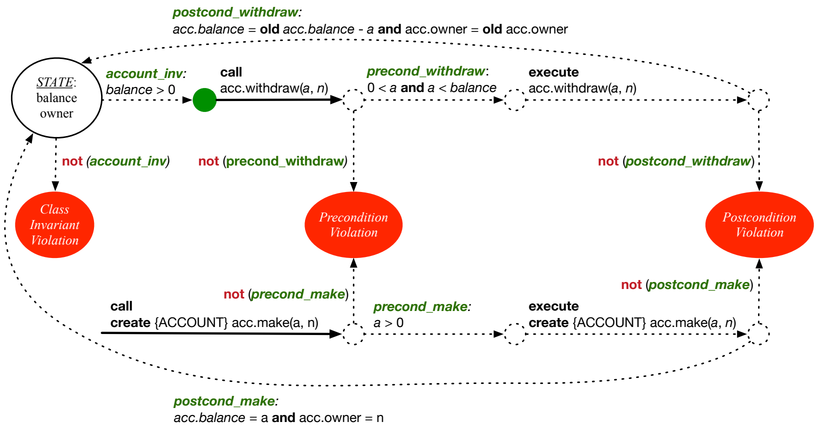
DbC in Eiffel: Anatomy of a Feature

```
some_command
   -- Description of the command.
  require
   -- List of tagged boolean expressions for preconditions
  local
   -- List of local variable declarations
  do
   -- List of instructions as implementation
  ensure
   -- List of tagged boolean expressions for postconditions
  end
```

- The *precondition* `require` clause may be omitted:
  - There's no precondition: any starting state is acceptable.
  - The precondition is equivalent to writing **`require`** ***true***
- The *postcondition* `ensure` clause may be omitted:
  - There's no postcondition: any resulting state is acceptable.
  - The postcondition is equivalent to writing **`ensure`** ***true***

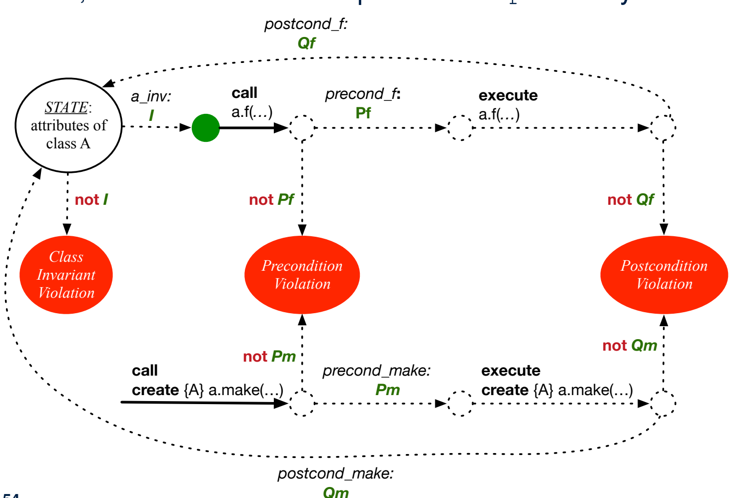
Runtime Monitoring of Contracts (1)

In the specific case of `ACCOUNT` class with creation procedure `make` and command `withdraw`:



Runtime Monitoring of Contracts (2)

In general, class `C` with creation procedure `cp` and any feature `f`:



Runtime Monitoring of Contracts (3)

- All *contracts* are specified as ***Boolean expressions***.
- Right before a feature call (e.g., *acc.withdraw(10)*):
  - The current state of *acc* is called the *pre-state*.
  - Evaluate feature `withdraw`'s *pre-condition* using current values of attributes and queries.
  - ***Cache*** values (**implicitly**) of all expressions involving the ***old*** keyword in the *post-condition*.

    e.g., cache the value of *old balance* via *old_balance := balance*
- Right after the feature call:
  - The current state of *acc* is called the *post-state*.
  - Evaluate class `ACCOUNT`'s *invariant* using current values of attributes and queries.
  - Evaluate feature `withdraw`'s *post-condition* using both current and ***"cached"*** values of attributes and queries.

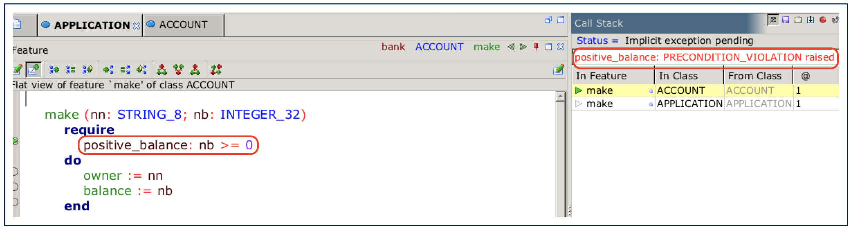
DbC in Eiffel: Precondition Violation (1.1)

The **client** need not handle all possible contract violations:

```
class BANK_APP
inherit
  ARGUMENTS
create
  make
feature -- Initialization
  make
    -- Run application.
  local
    alan: ACCOUNT
  do
    -- A precondition violation with tag "positive_balance"
    create {ACCOUNT} alan.make ("Alan", -10)
  end
end
```

By executing the above code, the runtime monitor of Eiffel Studio will report a *contract violation* (precondition violation with tag `"positive_balance"`).

DbC in Eiffel: Precondition Violation (1.2)



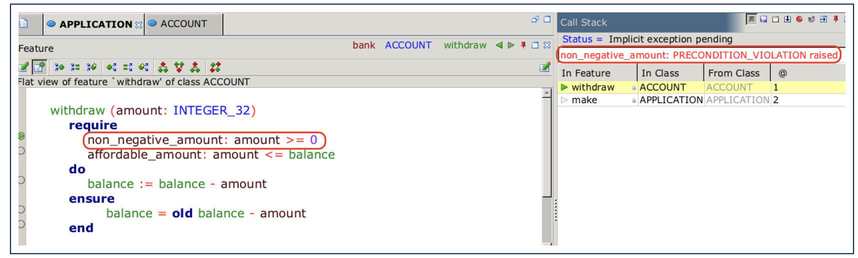
DbC in Eiffel: Precondition Violation (2.1)

The **client** need not handle all possible contract violations:

```
class BANK_APP
inherit
  ARGUMENTS
create
  make
feature -- Initialization
  make
    -- Run application.
  local
    mark: ACCOUNT
  do
    create {ACCOUNT} mark.make ("Mark", 100)
    -- A precondition violation with tag "non_negative_amount"
    mark.withdraw(-1000000)
  end
end
```

By executing the above code, the runtime monitor of Eiffel Studio will report a *contract violation* (precondition violation with tag "non_negative_amount").

DbC in Eiffel: Precondition Violation (2.2)



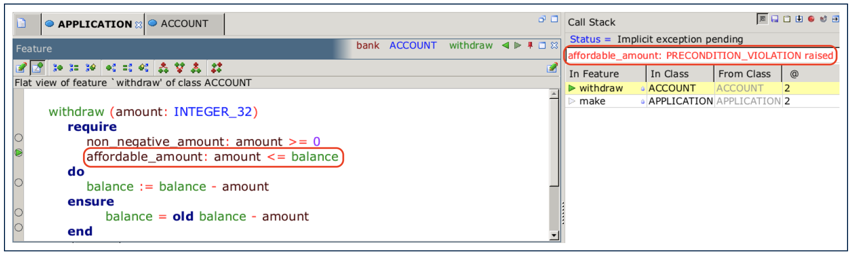
DbC in Eiffel: Precondition Violation (3.1)

The **client** need not handle all possible contract violations:

```
class BANK_APP
inherit
  ARGUMENTS
create
  make
feature -- Initialization
  make
    -- Run application.
  local
    tom: ACCOUNT
  do
    create {ACCOUNT} tom.make ("Tom", 100)
    -- A precondition violation with tag "affordable_amount"
    tom.withdraw(150)
  end
end
```

By executing the above code, the runtime monitor of Eiffel Studio will report a *contract violation* (precondition violation with tag "affordable_amount").

DbC in Eiffel: Precondition Violation (3.2)



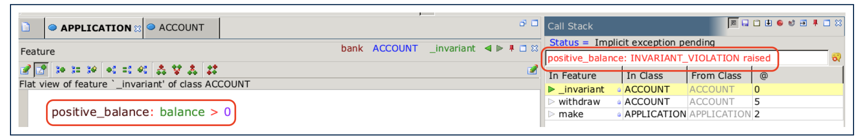
DbC in Eiffel: Class Invariant Violation (4.1)

The **client** need not handle all possible contract violations:

```
class BANK_APP
inherit
  ARGUMENTS
create
  make
feature -- Initialization
  make
    -- Run application.
  local
    jim: ACCOUNT
  do
    create {ACCOUNT} tom.make ("Jim", 100)
    jim.withdraw(100)
    -- A class invariant violation with tag "positive_balance"
  end
end
```

By executing the above code, the runtime monitor of Eiffel Studio will report a *contract violation* (class invariant violation with tag "positive_balance").

DbC in Eiffel: Class Invariant Violation (4.2)



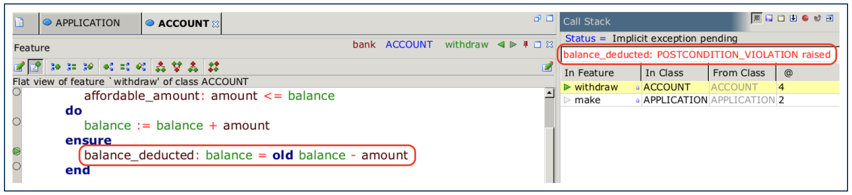
DbC in Eiffel: Postcondition Violation (5.1)

The **client** need not handle all possible contract violations:

```
class BANK_APP
inherit ARGUMENTS
create make
feature -- Initialization
  make
    -- Run application.
  local
    jeremy: ACCOUNT
  do
    -- Faulty implementation of withdraw in ACCOUNT:
    -- balance := balance + amount
    create {ACCOUNT} jeremy.make ("Jeremy", 100)
    jeremy.withdraw(150)
    -- A postcondition violation with tag "balance_deducted"
  end
end
```

By executing the above code, the runtime monitor of Eiffel Studio will report a *contract violation* (postcondition violation with tag "balance_deducted").

DbC in Eiffel: Postcondition Violation (5.2)



Index (1)

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Syntax of Eiffel: a Brief Overview

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Escape Sequences

Escape sequences are special characters to be placed in your program text.

- In Java, an escape sequence starts with a backward slash `\` e.g., `\n` for a new line character.
- In Eiffel, an escape sequence starts with a percentage sign `%` e.g., `%N` for a new line characgter.

See here for more escape sequences in Eiffel: `https://www.eiffel.org/doc/eiffel/Eiffel%20programming%20language%20syntax#Special_characters`

Commands, and Queries, and Features

- In a Java class:
  - **Attributes**: Data
  - **Mutators**: Methods that change attributes without returning
  - **Accessors**: Methods that access attribute values and returning
- In an Eiffel class:
  - Everything can be called a *feature*.
  - But if you want to be specific:
    - Use *attributes* for data
    - Use *commands* for mutators
    - Use *queries* for accessors

Operators: Assignment vs. Equality

- In Java:
  - Equal sign = is for assigning a value expression to some variable.
    e.g., `x = 5 * y` changes `x`'s value to `5 * y`
    This is actually controversial, since when we first learned about =, it means the mathematical equality between numbers.
  - Equal-equal == and bang-equal != are used to denote the equality and inequality.
    e.g., `x == 5 * y` evaluates to *true* if `x`'s value is equal to the value of `5 * y`, or otherwise it evaluates to *false*.
- In Eiffel:
  - Equal = and slash equal /= denote equality and inequality.
    e.g., `x = 5 * y` evaluates to *true* if `x`'s value is equal to the value of `5 * y`, or otherwise it evaluates to *false*.
  - We use := to denote variable assignment.
    e.g., `x := 5 * y` changes `x`'s value to `5 * y`
  - Also, you are not allowed to write shorthands like `x++`, just write `x := x + 1`.

Naming Conventions

- Cluster names: all lower-cases separated by underscores
  e.g., `root`, `model`, `tests`, `cluster_number_one`
- Classes/Type names: all upper-cases separated by underscores
  e.g., `ACCOUNT`, `BANK_ACCOUNT_APPLICATION`
- Feature names (attributes, commands, and queries): all lower-cases separated by underscores
  e.g., `account_balance`, `deposit_into`, `withdraw_from`

Attribute Declarations

- In Java, you write: `int i`, `Account acc`
- In Eiffel, you write: `i: INTEGER`, `acc: ACCOUNT`
  Think of : as the set membership operator $\in$:
  e.g., The declaration `acc: ACCOUNT` means object `acc` is a member of all possible instances of `ACCOUNT`.

Method Declaration

- **Command**

```
deposit (amount: INTEGER)
  do
    balance := balance + amount
  end
```

Notice that you don't use the return type `void`

- **Query**

```
sum_of (x: INTEGER; y: INTEGER): INTEGER
  do
    Result := x + y
  end
```

  - Input parameters are separated by semicolons ;
  - Notice that you don't use `return`; instead assign the return value to the pre-defined variable **Result**.

Operators: Logical Operators (1)

- Logical operators (what you learned from EECS1090) are for combining Boolean expressions.
- In Eiffel, we have operators that *EXACTLY* correspond to these logical operators:

	LOGIC	EIFFEL
Conjunction	$\wedge$	**and**
Disjunction	$\vee$	**or**
Implication	$\Rightarrow$	**implies**
Equivalence	$\equiv$	**=**

Review of Propositional Logic (1)

- A *proposition* is a statement of claim that must be of either *true* or *false*, but not both.
- Basic logical operands are of type Boolean: *true* and *false*.
- We use logical operators to construct compound statements.
  - Binary logical operators: conjunction ($\wedge$), disjunction ($\vee$), implication ($\Rightarrow$), and equivalence (a.k.a if-and-only-if $\iff$)

p	q	$p \wedge q$	$p \vee q$	$p \Rightarrow q$	$p \iff q$
true	*true*	*true*	*true*	*true*	*true*
true	*false*	*false*	*true*	*false*	*false*
false	*true*	*false*	*true*	*true*	*false*
false	*false*	*false*	*false*	*true*	*true*

  - Unary logical operator: negation ($\neg$)

p	$\neg p$
true	*false*
false	*true*

Review of Propositional Logic: Implication

- Written as $p \Rightarrow q$
- Pronounced as "p implies q"
- We call p the antecedent, assumption, or premise.
- We call q the consequence or conclusion.
- Compare the *truth* of $p \Rightarrow q$ to whether a contract is *honoured*: $p \approx$ promised terms; and $q \approx$ obligations.
- When the promised terms are met, then:
  - The contract is *honoured* if the obligations are fulfilled.
  - The contract is *breached* if the obligations are not fulfilled.
- When the promised terms are not met, then:
  - Fulfilling the obligation (q) or not ($\neg q$) does *not breach* the contract.

p	q	$p \Rightarrow q$
true	*true*	*true*
true	*false*	*false*
false	*true*	*true*
false	*false*	*true*

Review of Propositional Logic (2)

- **Axiom**: Definition of $\Rightarrow$

$$p \Rightarrow q \equiv \neg p \lor q$$

- **Theorem**: Identity of $\Rightarrow$

$$true \Rightarrow p \equiv p$$

- **Theorem**: Zero of $\Rightarrow$

$$false \Rightarrow p \equiv true$$

- **Axiom**: De Morgan

$$\neg(p \land q) \equiv \neg p \lor \neg q$$
$$\neg(p \lor q) \equiv \neg p \land \neg q$$

- **Axiom**: Double Negation

$$p \equiv \neg\,(\neg\, p)$$

- **Theorem**: Contrapositive

$$p \Rightarrow q \equiv \neg q \Rightarrow \neg p$$

Review of Predicate Logic (1)

- A *predicate* is a *universal* or *existential* statement about objects in some universe of disclosure.
- Unlike propositions, predicates are typically specified using *variables*, each of which declared with some *range* of values.
- We use the following symbols for common numerical ranges:
  - $\mathbb{Z}$: the set of integers
  - $\mathbb{N}$: the set of natural numbers
- Variable(s) in a predicate may be *quantified*:
  - *Universal quantification* :
    All values that a variable may take satisfy certain property.
    e.g., Given that i is a natural number, i is *always* non-negative.
  - *Existential quantification* :
    Some value that a variable may take satisfies certain property.
    e.g., Given that i is an integer, i *can be* negative.

Review of Predicate Logic (2.1)

- A *universal quantification* has the form $(\forall X \mid R \bullet P)$
  - X is a list of variable *declarations*
  - R is a *constraint on ranges* of declared variables
  - P is a *property*
  - $(\forall X \mid R \bullet P) \equiv (\forall X \bullet R \Rightarrow P)$
    e.g., $(\forall X \mid True \bullet P) \equiv (\forall X \bullet True \Rightarrow P) \equiv (\forall X \bullet P)$
    e.g., $(\forall X \mid False \bullet P) \equiv (\forall X \bullet False \Rightarrow P) \equiv (\forall X \bullet True) \equiv True$
- *For all* (combinations of) values of variables declared in X that satisfies R, it is the case that P is satisfied.
  - $\forall i \mid i \in \mathbb{N} \bullet i \geq 0$ [*true*]
  - $\forall i \mid i \in \mathbb{Z} \bullet i \geq 0$ [*false*]
  - $\forall i, j \mid i \in \mathbb{Z} \land j \in \mathbb{Z} \bullet i < j \lor i > j$ [*false*]
- The range constraint of a variable may be moved to where the variable is declared.
  - $\forall i : \mathbb{N} \bullet i \geq 0$
  - $\forall i : \mathbb{Z} \bullet i \geq 0$
  - $\forall i, j : \mathbb{Z} \bullet i < j \lor i > j$

Review of Predicate Logic (2.2)

- An *existential quantification* has the form $(\exists X \mid R \bullet P)$
  - X is a list of variable *declarations*
  - R is a *constraint on ranges* of declared variables
  - P is a *property*
  - $(\exists X \mid R \bullet P) \equiv (\exists X \bullet R \land P)$
    e.g., $(\exists X \mid True \bullet P) \equiv (\exists X \bullet True \land P) \equiv (\forall X \bullet P)$
    e.g., $(\exists X \mid False \bullet P) \equiv (\exists X \bullet False \land P) \equiv (\exists X \bullet False) \equiv False$
- *There exists* a combination of values of variables declared in X that satisfies R and P.
  - $\exists i \mid i \in \mathbb{N} \bullet i \geq 0$ [*true*]
  - $\exists i \mid i \in \mathbb{Z} \bullet i \geq 0$ [*true*]
  - $\exists i, j \mid i \in \mathbb{Z} \land j \in \mathbb{Z} \bullet i < j \lor i > j$ [*true*]
- The range constraint of a variable may be moved to where the variable is declared.
  - $\exists i : \mathbb{N} \bullet i \geq 0$
  - $\exists i : \mathbb{Z} \bullet i \geq 0$
  - $\exists i, j : \mathbb{Z} \bullet i < j \lor i > j$

Predicate Logic (3)

- Conversion between ∀ and ∃

$$(\forall X \mid R \bullet P) \iff \neg(\exists X \bullet R \Rightarrow \neg P)$$
$$(\exists X \mid R \bullet P) \iff \neg(\forall X \bullet R \Rightarrow \neg P)$$

- Range Elimination

$$(\forall X \mid R \bullet P) \iff (\forall X \bullet R \Rightarrow P)$$
$$(\exists X \mid R \bullet P) \iff (\exists X \bullet R \wedge P)$$

Operators: Logical Operators (2)

- How about Java?
  - Java does not have an operator for logical implication.
  - The `==` operator can be used for logical equivalence.
  - The `&&` and `||` operators only **approximate** conjunction and disjunction, due to the ***short-circuit effect*** *(SCE)*:
    - When evaluating `e1 && e2`, if `e1` already evaluates to *false*, then `e1` will **not** be evaluated.
      e.g., In `(y != 0) && (x / y > 10)`, the SCE guards the division against division-by-zero error.
    - When evaluating `e1 || e2`, if `e1` already evaluates to *true*, then `e1` will **not** be evaluated.
      e.g., In `(y == 0) || (x / y > 10)`, the SCE guards the division against division-by-zero error.
  - However, in math, we always evaluate both sides.
- In Eiffel, we also have the version of operators with SCE:

	short-circuit conjunction	short-circuit disjunction
Java	`&&`	`||`
Eiffel	**and then**	**or else**

Operators: Division and Modulo

	Division	Modulo (Remainder)
Java	`20 / 3` is 6	`20 % 3` is 2
Eiffel	`20 // 3` is 6	`20 \\ 3` is 2

Class Declarations

- In Java:

```
class BankAccount {
  /* attributes and methods */
}
```

- In Eiffel:

```
class BANK_ACCOUNT
  /* attributes, commands, and queries */
end
```

Class Constructor Declarations (1)

- In Eiffel, constructors are just commands that have been *explicitly* declared as **creation features**:

```
class BANK_ACCOUNT
-- List names commands that can be used as constructors
create
 make
feature -- Commands
 make (b: INTEGER)
   do balance := b end
 make2
   do balance := 10 end
end
```

- Only the command `make` can be used as a constructor.
- Command `make2` is not declared explicitly, so it cannot be used as a constructor.

Creations of Objects (1)

- In Java, we use a constructor `Accont(int b)` by:
  - Writing `Account acc = new Account(10)` to create a named object `acc`
  - Writing `new Account(10)` to create an anonymous object
- In Eiffel, we use a creation feature (i.e., a command explicitly declared under `create`) `make (int b)` in class `ACCOUNT` by:
  - Writing `create {ACCOUNT} acc.make (10)` to create a named object `acc`
  - Writing `create {ACCOUNT}.make (10)` to create an anonymous object
- Writing `create {ACCOUNT} acc.make (10)`

  is really equivalent to writing

  `acc := create {ACCOUNT}.make (10)`

Selections (1)

```
if B1 then
  -- B1
  -- do something
elseif B2 then
  -- B2 ∧ (¬B1)
  -- do something else
else
  -- (¬B1) ∧ (¬B2)
  -- default action
end
```


Selections (2)

An *if-statement* is considered as:
- An *instruction* if its branches contain *instructions*.
- An *expression* if its branches contain Boolean *expressions*.

```
class
 FOO
feature --Attributes
 x, y: INTEGER
feature -- Commands
 command
   -- A command with if-statements in implementation and contracts.
  require
   if x \\ 2 /= 0 then True else False end -- Or: x \\ 2 /= 0
  do
   if x > 0 then y := 1 elseif x < 0 then y := -1 else y := 0 end
  ensure
   y = if old x > 0 then 1 elseif old x < 0 then -1 else 0 end
   -- Or: (old x > 0 implies y = 1)
   -- and (old x < 0 implies y = -1) and (old x = 0 implies y = 0)
  end
end
```

Loops (1)

- In Java, the Boolean conditions in `for` and `while` loops are **stay** conditions.

```
void printStuffs() {
  int i = 0;
  while( i < 10  /* stay condition */) {
    System.out.println(i);
    i = i + 1;
  }
}
```

- In the above Java loop, we *stay* in the loop as long as `i < 10` is true.
- In Eiffel, we think the opposite: we *exit* the loop as soon as `i >= 10` is true.

Loops (2)

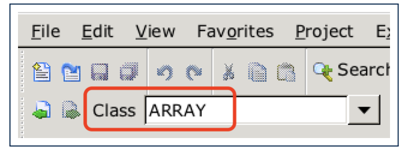
In Eiffel, the Boolean conditions you need to specify for loops are **exit** conditions (logical negations of the stay conditions).

```
print_stuffs
  local
    i: INTEGER
  do
    from
      i := 0
    until
      i >= 10  -- exit condition
    loop
      print (i)
      i := i + 1
    end -- end loop
  end -- end command
```

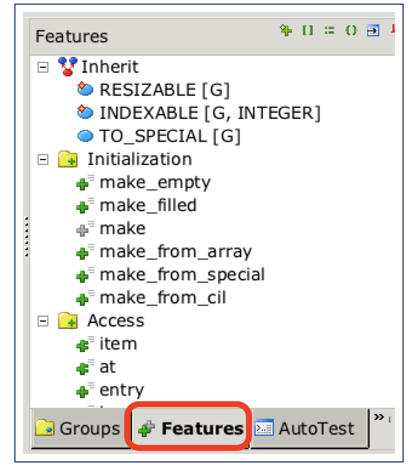
- Don't put `()` after a command or query with no input parameters.
- Local variables must all be declared in the beginning.

Library Data Structures

Enter a DS name.



Explore supported features.



Data Structures: Arrays

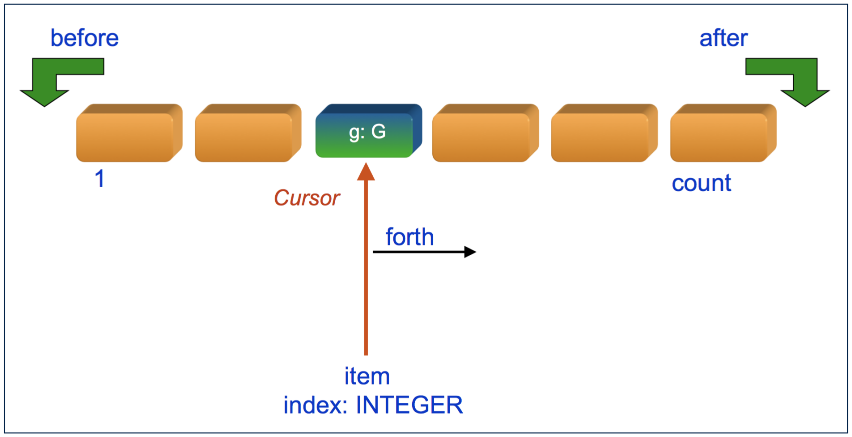
- Creating an empty array:

```
local a: ARRAY[INTEGER]
do create {ARRAY[INTEGER]} a.make_empty
```

  - This creates an array of `lower` and `upper` indices 1 and 0.
  - Size of array `a`: `a.upper - a.lower + 1`.
- Typical loop structure to iterate through an array:

```
local
  a: ARRAY[INTEGER]
  i, j: INTEGER
do
  ...
from
  j := a.lower
until
  j > a.upper
do
  i := a [j]
  j := j + 1
end
```

Data Structures: Linked Lists (1)



Data Structures: Linked Lists (2)

- Creating an empty linked list:

```
local
  list: LINKED_LIST[INTEGER]
do
  create {LINKED_LIST[INTEGER]} list.make
```

- Typical loop structure to iterate through a linked list:

```
local
  list: LINKED_LIST[INTEGER]
  i: INTEGER
do
  ...
from
  list.start
until
  list.after
do
  i := list.item
  list.forth
end
```


Iterable Structures

- Eiffel collection types (like in Java) are *iterable*.
- If indices are irrelevant for your application, use:

  across ... ***as*** ... ***loop*** ... ***end***

  e.g.,

```
...
local
  a: ARRAY[INTEGER]
  l: LINKED_LIST[INTEGER]
  sum1, sum2: INTEGER
do
  ...
  across a as cursor loop sum1 := sum1 + cursor.item end
  across l as cursor loop sum2 := sum2 + cursor.item end
  ...
end
```


Using `across` for Quantifications (1)

- ***across*** ... ***as*** ... ***all*** ... ***end***

  A Boolean expression acting as a universal quantification (∀)

```
1  local
2    allPositive: BOOLEAN
3    a: ARRAY[INTEGER]
4  do
5    ...
6    Result :=
7      across
8        a.lower |..| a.upper as i
9      all
10       a [i.item] > 0
11     end
```

  - **L8**: `a.lower |..| a.upper` denotes a list of integers.
  - **L8**: `as i` declares a list cursor for this list.
  - **L10**: `i.item` denotes the value pointed to by cursor `i`.
- **L9**: Changing the keyword **all** to ***some*** makes it act like an existential quantification ∃.

Using across for Quantifications (2)

```
class
  CHECKER
feature -- Attributes
  collection: ITERABLE [INTEGER] -- ARRAY, LIST, HASH_TABLE
feature -- Queries
  is_all_positive: BOOLEAN
      -- Are all items in collection positive?
    do
      ...
    ensure
      across
        collection as cursor
      all
        cursor.item > 0
      end
  end
```

- Using **all** corresponds to a universal quantification (i.e., $\forall$).
- Using **some** corresponds to an existential quantification (i.e., $\exists$).

Using across for Quantifications (3)

```
class BANK
...
  accounts: LIST [ACCOUNT]
  binary_search (acc_id: INTEGER): ACCOUNT
      -- Search on accounts sorted in non-descending order.
    require
      -- ∀i : INTEGER | 1 ≤ i < accounts.count • accounts[i].id ≤ accounts[i + 1].id
      across
        1 |..| (accounts.count - 1) as cursor
      all
        accounts [cursor.item].id <= accounts [cursor.item + 1].id
      end
    do
      ...
    ensure
      Result.id = acc_id
    end
```


Using across for Quantifications (4)

```
class BANK
...
  accounts: LIST [ACCOUNT]
  contains_duplicate: BOOLEAN
      -- Does the account list contain duplicate?
    do
      ...
    ensure
      ∀i, j : INTEGER |
        1 ≤ i ≤ accounts.count ∧ 1 ≤ j ≤ accounts.count •
          accounts[i] ~ accounts[j] ⇒ i = j
    end
```

- **Exercise:** Convert this mathematical predicate for postcondition into Eiffel.
- **Hint:** Each **across** construct can only introduce one dummy variable, but you may nest as many **across** constructs as necessary.

Equality

- To compare references between two objects, use `=`.
- To compare "contents" between two objects ***of the same type***, use the *redefined* version of `is_equal` feature.
- You may also use the binary operator `~`

  `o1 ~ o2` evaluates to:
  - *true* — if both `o1` and `o2` are void
  - *false* — if one is void but not the other
  - `o1.is_equal(o2)` — if both are not void

Use of ~: Caution

```
1  class
2    BANK
3  feature -- Attribute
4    accounts: ARRAY[ACCOUNT]
5  feature -- Queries
6    get_account (id: STRING): detachable ACCOUNT
7        -- Account object with 'id'.
8      do
9        across
10         accounts as cursor
11       loop
12         if cursor.item ~ id then
13           Result := cursor.item
14         end
15       end
16     end
17 end
```

L15 should be: `cursor.item.id ~ id`

Index (1)

Index (2)

Index (3)

Common Eiffel Errors: Contracts vs. Implementations

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Contracts vs. Implementations: Definitions

In Eiffel, there are two categories of constructs:

- ***Implementations***
  - are step-by-step **instructions** that have *side-effects*

    e.g., `... := ...`, `across ... as ... loop ... end`

  - change attribute values
  - do not return values
  - ≈ commands
- ***Contracts***
  - are Boolean **expressions** that have *no side-effects*

    e.g., `... = ...`, `across ... as ... all ... end`

  - use attribute and parameter values to specify a condition
  - return a Boolean value (i.e., *True* or *False*)
  - ≈ queries

Contracts vs. Implementations: Where?

- Instructions for *Implementations*: $inst_1$, $inst_2$
- Boolean expressions for Contracts: exp_1, exp_2, exp_3, exp_4, exp_5

```
class
    ACCOUNT
feature -- Queries
    balance: INTEGER
        require
            exp1
        do
            inst1
        ensure
            exp2
        end
```

```
feature -- Commands
    withdraw
        require
            exp3
        do
            inst2
        ensure
            exp4
        end
invariant
    exp5
end -- end of class ACCOUNT
```


Implementations: Instructions with No Return Values

- Assignments

```
balance := balance + a
```

- Selections with branching instructions:

```
if a > 0 then acc.deposit (a) else acc.withdraw (-a) end
```

- Loops

```
from
  i := a.lower
until
  i > a.upper
loop
  Result :=
    Result + a[i]
  i := i + 1
end
```

```
from
  list.start
until
  list.after
loop
  list.item.wdw(10)
  list.forth
end
```

```
across
  list as cursor
loop
  sum :=
    sum + cursor.item
end
```

Contracts: Expressions with Boolean Return Values

- Relational Expressions (using =, /=, ~, /~, >, <, >=, <=)

```
a > 0
```

- Binary Logical Expressions (using **and**, **and then**, **or**, **or else**, **implies**)

```
(a.lower <= index) and (index <= a.upper)
```

- Logical Quantification Expressions (using **all**, **some**)

```
across
  a.lower |..| a.upper as cursor
all
  a [cursor.item] >= 0
end
```

- **old** keyword can only appear in postconditions (i.e., **ensure**).

```
balance = old balance + a
```


Contracts: Common Mistake (1)

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      balance := old balance - a
    end
...
```

Colon-Equal sign (`:=`) is used to write assignment instructions.

Contracts: Common Mistake (1) Fixed

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      balance = old balance - a
    end
...
```


Contracts: Common Mistake (2)

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      across
        a as cursor
      loop
        ...
      end
...
```

across . . . **loop** . . . **end** is used to create loop instructions.

Contracts: Common Mistake (2) Fixed

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      across
        a as cursor
      all -- if you meant ∀, or use some if you meant ∃
        ... -- A Boolean expression is expected here!
      end
...
```


Contracts: Common Mistake (3)

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      old balance - a
    end
...
```

Contracts can only be specified as Boolean expressions.

Contracts: Common Mistake (3) Fixed

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      ...
    ensure
      postcond_1: balance = old balance - a
      postcond_2: old balance > 0
    end
...
```


Contracts: Common Mistake (4)

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    require
      old balance > 0
    do
      ...
    ensure
      ...
    end
...
```

- Only *postconditions* may use the **old** keyword to specify *the relationship between pre-state values* (before the execution of *withdraw*) *and post-state values* (after the execution of *withdraw*).
- *Pre-state values* (right before the feature is executed) are indeed the *old* values, so there's no need to qualify them!

Contracts: Common Mistake (4) Fixed

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    require
      balance > 0
    do
      ...
    ensure
      ...
    end
...
```


Contracts: Common Mistake (5)

```
class LINEAR_CONTAINER
create make
feature -- Attributes
  a: ARRAY[STRING]
feature -- Queries
  count: INTEGER do Result := a.count end
  get (i: INTEGER): STRING do Result := a[i] end
feature -- Commands
  make do create a.make_empty end
  update (i: INTEGER; v: STRING)
  do ...
  ensure -- Others Unchanged
      across
        1 |..| count as j
      all
        j.item /= i implies old get(j.item) ~ get(j.item)
      end
  end
end
```

Compilation Error:

- Expression value to be cached before executing `update`?
  [`Current.get(j.item)`]
- But, in the ***pre-state***, integer cursor `j` does not exist!

Contracts: Common Mistake (5) Fixed

```
class LINEAR_CONTAINER
create make
feature -- Attributes
  a: ARRAY[STRING]
feature -- Queries
  count: INTEGER do Result := a.count end
  get (i: INTEGER): STRING do Result := a[i] end
feature -- Commands
  make do create a.make_empty end
  update (i: INTEGER; v: STRING)
  do ...
  ensure -- Others Unchanged
      across
        1 |..| count as j
      all
        j.item /= i implies (old Current).get(j.item) ~ get(j.item)
      end
  end
end
```

- The idea is that the **old** expression should not involve the local cursor variable `j` that is introduced in the postcondition.
- Whether to put (**old** *Current.twin*) or (**old** *Current.deep_twin*) is up to your need.

Implementations: Common Mistake (1)

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      balance = balance + 1
    end
  ...
```

- Equal sign (=) is used to write Boolean expressions.
- In the context of implementations, Boolean expression values must appear:
  - on the RHS of an *assignment*;
  - as one of the *branching conditions* of an if-then-else statement; or
  - as the *exit condition* of a loop instruction.

Implementations: Common Mistake (1) Fixed

```
class
  ACCOUNT
feature
  withdraw (a: INTEGER)
    do
      balance := balance + 1
    end
...
```


Implementations: Common Mistake (2)

```
class
  BANK
feature
  min_credit: REAL
  accounts: LIST[ACCOUNT]

  no_warning_accounts: BOOLEAN
    do
      across
        accounts as cursor
      all
        cursor.item.balance > min_credit
      end
    end
...
```

Again, in implementations, Boolean expressions cannot appear alone without their values being "captured".

Implementations: Common Mistake (2) Fixed

```
1  class
2    BANK
3  feature
4    min_credit: REAL
5    accounts: LIST[ACCOUNT]
6
7    no_warning_accounts: BOOLEAN
8      do
9        Result :=
10         across
11           accounts as cursor
12         all
13           cursor.item.balance > min_credit
14         end
15     end
16 ...
```

Rewrite L10 – L14 using **across** ... **as** ... ***some*** ... **end**.

Hint: $\forall x \bullet P(x) \equiv \neg(\exists x \bullet \neg P(x))$

Implementations: Common Mistake (3)

```
class
  BANK
feature
  accounts: LIST[ACCOUNT]

  total_balance: REAL
    do
      Result :=
        across
          accounts as cursor
        loop
          Result := Result + cursor.item.balance
        end
      ...
    end
...
```

In implementations, since instructions do not return values, they cannot be used on the RHS of assignments.

Implementations: Common Mistake (3) Fixed

```
class
  BANK
feature
  accounts: LIST[ACCOUNT]

  total_balance: REAL
    do
      across
        accounts as cursor
      loop
        Result := Result + cursor.item.balance
      end
    end
```


Index (1)

Index (2)

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

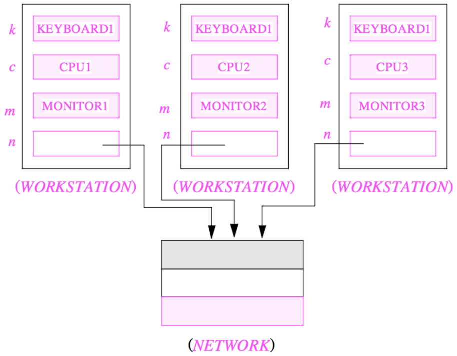
EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Expanded Class: Modelling

- We may want to have objects which are:
  - Integral parts of some other objects
  - ***Not*** shared among objects

  e.g., Each workstation has its own CPU, monitor, and keyword.
  All workstations share the same network.



Expanded Class: Programming (2)

```
class KEYBOARD ... end class CPU ... end
class MONITOR ... end class NETWORK ... end
class WORKSTATION
  k: expanded KEYBOARD
  c: expanded CPU
  m: expanded MONITOR
  n: NETWORK
end
```

Alternatively:

```
expanded class KEYBOARD ... end
expanded class CPU ... end
expanded class MONITOR ... end
class NETWORK ... end
class WORKSTATION
  k: KEYBOARD
  c: CPU
  m: MONITOR
  n: NETWORK
end
```


Expanded Class: Programming (3)

```
expanded class
  B
feature
  change_i (ni: INTEGER)
    do
      i := ni
    end
feature
  i: INTEGER
end
```

```
1  test_expanded: BOOLEAN
2    local
3      eb1, eb2: B
4    do
5      Result := eb1.i = 0 and eb2.i = 0
6      check Result end
7      Result := eb1 = eb2
8      check Result end
9      eb2.change_i (15)
10     Result := eb1.i = 0 and eb2.i = 15
11     check Result end
12     Result := eb1 /= eb2
13     check Result end
14   end
```

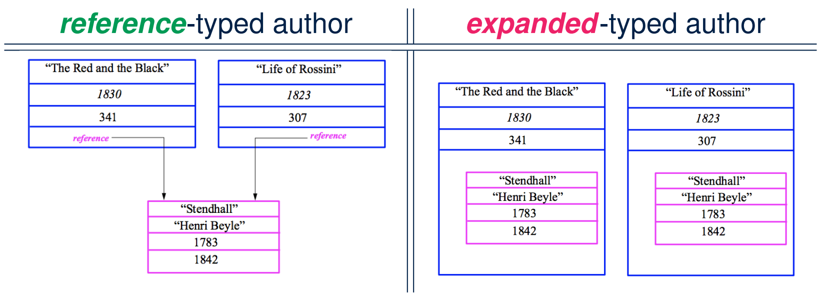
- **L5**: object of expanded type is automatically initialized.
- **L9 & L10**: no sharing among objects of expanded type.
- **L7 & L12**: = between expanded objects compare their contents.

Reference vs. Expanded (1)

- Every entity must be declared to be of a certain type (based on a class).
- Every type is either ***referenced*** or ***expanded***.
- In ***reference*** types:
  - y denotes ***a reference*** to some object
  - x := y attaches x to same object as does y
  - x = y compares references
- In ***expanded*** types:
  - y denotes ***some object*** (of expanded type)
  - x := y copies contents of y into x
  - x = y compares contents [x ~ y]

Reference vs. Expanded (2)

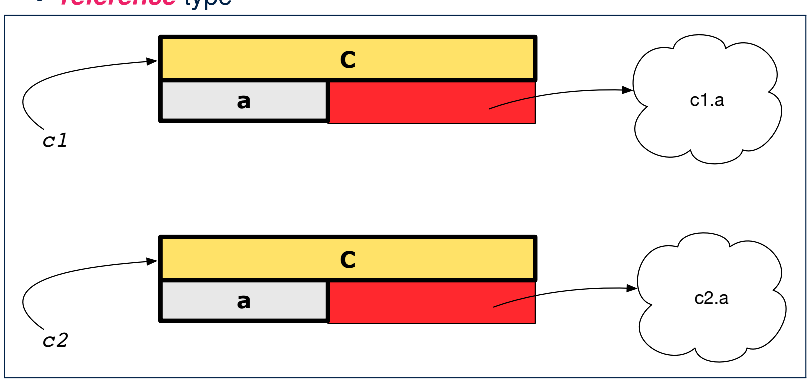
Problem: Every published book has an author. Every author may publish more than one books. Should the author field of a book ***reference***-typed or ***expanded***-typed?



Copying Objects

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

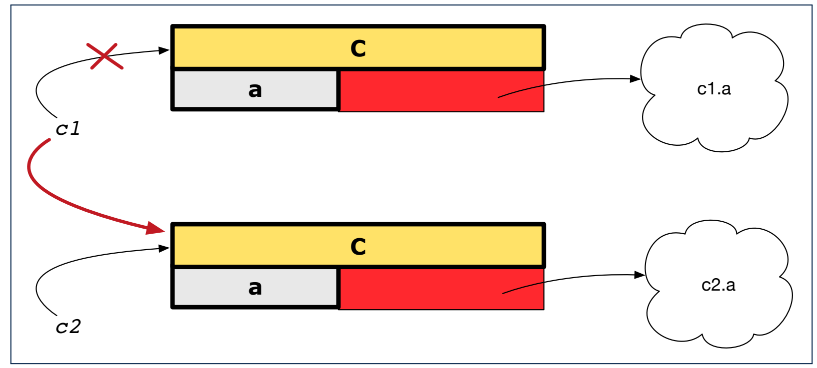
- There is only one attribute `a` declared in class `C`.
- `c1.a` and `c2.a` may be of either:
  - ***expanded*** type or
  - ***reference*** type



Copying Objects: Reference Copy

Reference Copy `c1 := c2`

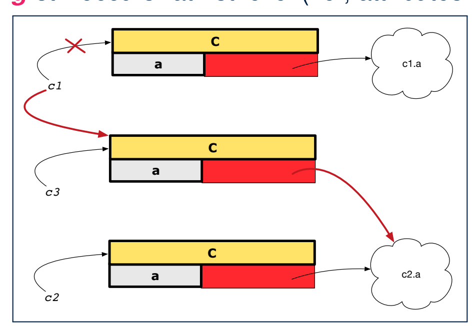
- Copy the address stored in variable `c2` and store it in `c1`.
  ⇒ Both `c1` and `c2` point to the same object.
  ⇒ Updates performed via `c1` also visible to `c2`. [***aliasing***]



Copying Objects: Shallow Copy

Shallow Copy `c1 := c2.twin`

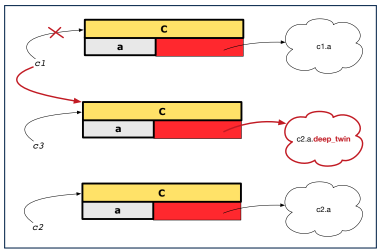
- Create a temporary, behind-the-scene object `c3` of type `C`.
- Initialize each attribute `a` of `c3` via ***reference copy***: `c3.a := c2.a`
- Make a ***reference copy*** of `c3`: `c1 := c3`
  ⇒ `c1` and `c2` ***are not*** pointing to the same object. [`c1 /= c2`]
  ⇒ `c1.a` and `c2.a` ***are*** 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 expanded (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.



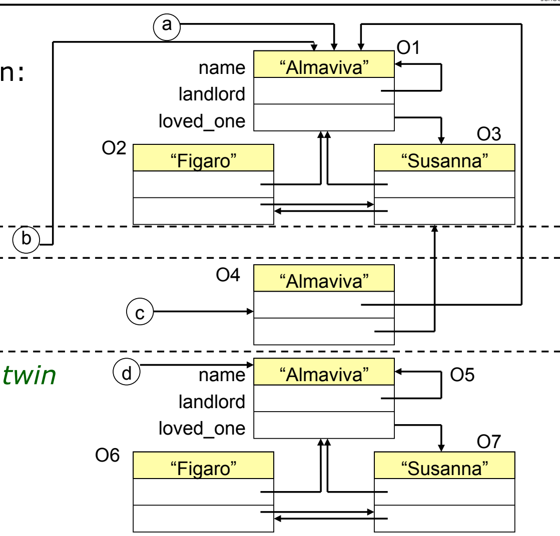
Copying Objects

- Initial situation:
- Result of:

b := a

c := a.twin

d := a.deep_twin



Example: Collection Objects (1)

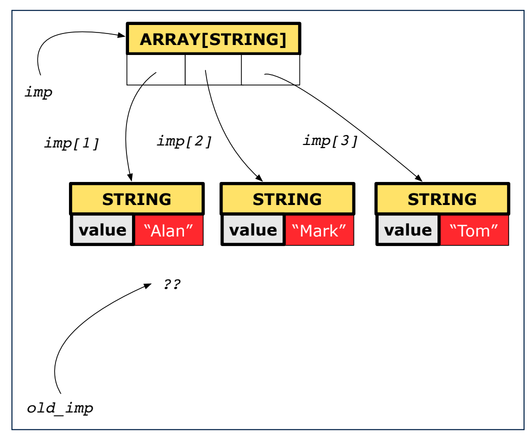
- In any OOPL, when a variable is declared of a ***type*** that corresponds to a ***known class*** (e.g., `STRING`, `ARRAY`, `LINKED_LIST`, etc.):

  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)
  ...
```


Example: Collection Objects (2)

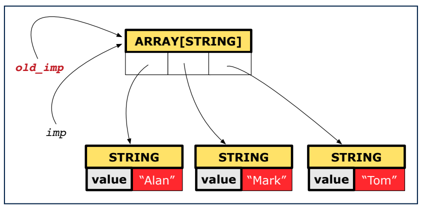
- Variables `imp` and `old_imp` store address(es) of some array(s).
- Each "slot" of these arrays stores a `STRING` object's address.



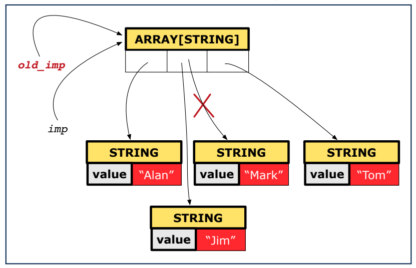
Reference Copy of Collection Object

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

Before Executing L3



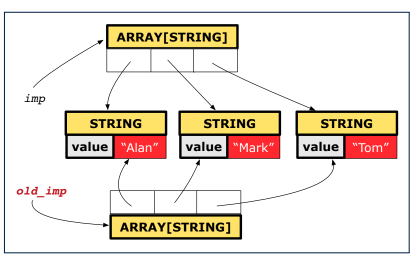
After Executing L3



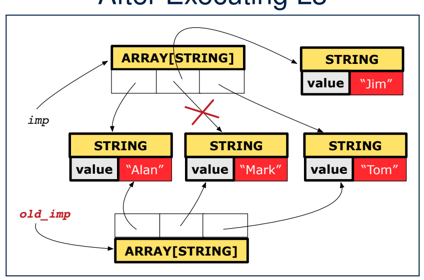
Shallow Copy of Collection Object (1)

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

Before Executing L3



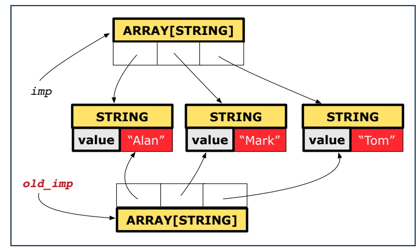
After Executing L3



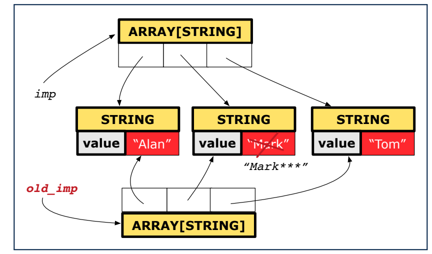
Shallow Copy of Collection Object (2)

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

Before Executing L3



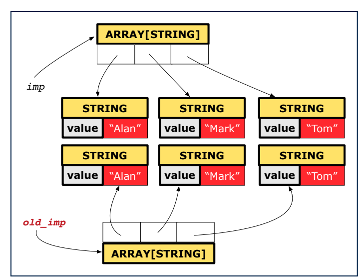
After Executing L3



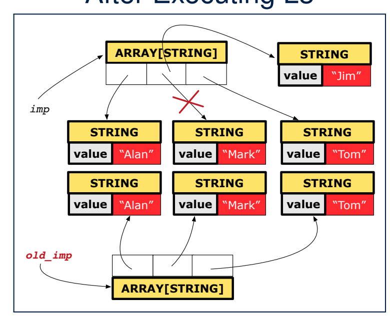
Deep Copy of Collection Object (1)

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

Before Executing L3



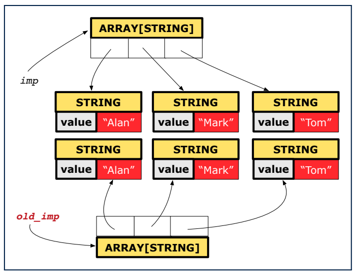
After Executing L3



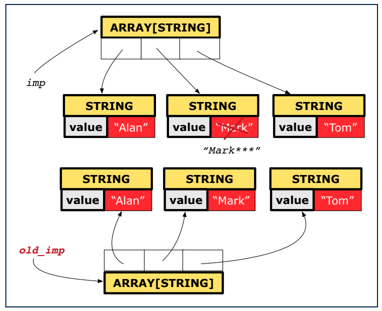
Deep Copy of Collection Object (2)

```
1 old_imp := imp.deep_twin
2 Result := old_imp = imp  -- Result = false
3 imp[2].append ("***")
4 Result :=
5   across 1 |..| imp.count as j
6   all imp [j.item] ~ old_imp [j.item] 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** *balance* = *balance* – *a* [*old_balance* := *balance*]

    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*].*id* [*old_accounts* := *accounts*]

    e.g., (**old** *Current*).*accounts*[*i*].*id* [*old_current* := *Current*]
- 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 as acc some acc.item.owner ~ n end
        -- not (across accounts as acc all acc.item.owner /~ n end)
    do ...
    ensure Result.owner ~ n
    end
  add (n: STRING)
    require -- the input name does not exist
      non_existing: across accounts as acc all acc.item.owner /~ n end
        -- not (across accounts as acc some acc.item.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

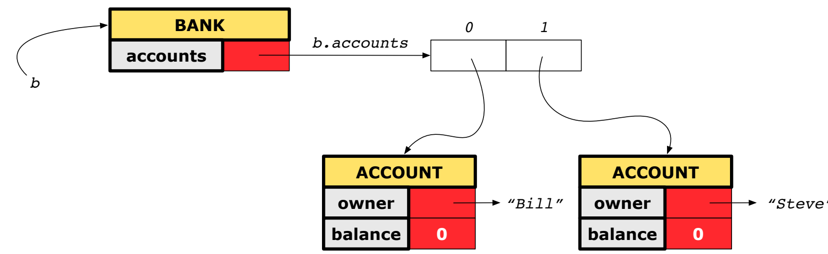
We examine 5 different versions of a command

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 as acc some acc.item.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:
        account_of (n).balance = old 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 as acc some acc.item.owner ~ n end
  local i: INTEGER
  do
   -- same loop as in version 1

   -- wrong implementation: also deposit in the first account
   accounts[accounts.lower].deposit(a)
  ensure
   num_of_accounts_unchanged:
    accounts.count = old accounts.count
   balance_of_n_increased:
    account_of (n).balance = old 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 as acc some acc.item.owner ~ n end
    local i: INTEGER
    do
      -- same loop as in version 1
      -- wrong implementation: also deposit in the first account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        account_of(n).balance = old account_of(n).balance + a
      others_unchanged :
        across old accounts as cursor
        all cursor.item.owner /~ n implies
              cursor.item ~ account_of (cursor.item.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 as acc some acc.item.owner ~ n end
    local i: INTEGER
    do
      -- same loop as in version 1
      -- wrong implementation: also deposit in the first account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        account_of (n).balance = old account_of (n).balance + a
      others_unchanged :
        across old accounts.twin as cursor
        all cursor.item.owner /~ n implies
              cursor.item ~ account_of (cursor.item.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 as acc some acc.item.owner ~ n end
      local i: INTEGER
    do
      -- same loop as in version 1
      -- wrong implementation: also deposit in the first account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        account_of (n).balance = old account_of (n).balance + a
      others_unchanged :
        across old accounts.deep_twin as cursor
        all cursor.item.owner /~ n implies
              cursor.item ~ account_of (cursor.item.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

Case Type	Passed	Total
FAILED (4 failed & 1 passed out of 5)		
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)

Use of Generic Parameters
Iterator and Singleton Patterns

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Generic Collection Class: Motivation (1)

```
class STRING_STACK
feature {NONE} -- Implementation
  imp: ARRAY[ STRING ] ; i: INTEGER
feature -- Queries
  count: INTEGER do Result := i end
    -- Number of items on stack.
  top: STRING do Result := imp [i] end
    -- Return top of stack.
feature -- Commands
  push (v: STRING ) do imp[i] := v; i := i + 1 end
    -- Add 'v' to top of stack.
  pop do i := i - 1 end
    -- Remove top of stack.
end
```

- Does how we implement integer stack operations (e.g., `top`, `push`, `pop`) depends on features specific to element type `STRING` (e.g., `at`, `append`)? [***NO!***]
- How would you implement another class `ACCOUNT_STACK`?

Generic Collection Class: Motivation (2)

```
class ACCOUNT _STACK
feature {NONE} -- Implementation
  imp: ARRAY[ ACCOUNT ] ; i: INTEGER
feature -- Queries
  count: INTEGER do Result := i end
    -- Number of items on stack.
  top: ACCOUNT do Result := imp [i] end
    -- Return top of stack.
feature -- Commands
  push (v: ACCOUNT ) do imp[i] := v; i := i + 1 end
    -- Add 'v' to top of stack.
  pop do i := i - 1 end
    -- Remove top of stack.
end
```

- Does how we implement integer stack operations (e.g., `top`, `push`, `pop`) depends on features specific to element type `ACCOUNT` (e.g., `deposit`, `withdraw`)? [***NO!***]
- A *collection* (e.g., table, tree, graph) is meant for the ***storage*** and ***retrieval*** of elements, not how those elements are manipulated.

Generic Collection Class: Supplier

- Your design ***"smells"*** if you have to create an ***almost identical*** new class (hence *code duplicates*) for every stack element type you need (e.g., `INTEGER`, `CHARACTER`, `PERSON`, etc.).
- Instead, as **supplier**, use *G* to *parameterize* element type:

```
class STACK [G]
feature {NONE} -- Implementation
  imp: ARRAY[ G ] ; i: INTEGER
feature -- Queries
  count: INTEGER do Result := i end
    -- Number of items on stack.
  top: G do Result := imp [i] end
    -- Return top of stack.
feature -- Commands
  push (v: G ) do imp[i] := v; i := i + 1 end
    -- Add 'v' to top of stack.
  pop do i := i - 1 end
    -- Remove top of stack.
end
```


Generic Collection Class: Client (1.1)

As **client**, declaring `ss: STACK[ STRING ]` instantiates every occurrence of `G` as `STRING`.

```
class STACK [G̸ STRING]
feature {NONE} -- Implementation
  imp: ARRAY[ G̸ STRING ] ; i: INTEGER
feature -- Queries
  count: INTEGER do Result := i end
    -- Number of items on stack.
  top: G̸ STRING do Result := imp [i] end
    -- Return top of stack.
feature -- Commands
  push (v: G̸ STRING ) do imp[i] := v; i := i + 1 end
    -- Add 'v' to top of stack.
  pop do i := i - 1 end
    -- Remove top of stack.
end
```


Generic Collection Class: Client (1.2)

As **client**, declaring `ss: STACK[ ACCOUNT ]` instantiates every occurrence of `G` as `ACCOUNT`.

```
class STACK [G̸ ACCOUNT]
feature {NONE} -- Implementation
  imp: ARRAY[ G̸ ACCOUNT ] ; i: INTEGER
feature -- Queries
  count: INTEGER do Result := i end
    -- Number of items on stack.
  top: G̸ ACCOUNT do Result := imp [i] end
    -- Return top of stack.
feature -- Commands
  push (v: G̸ ACCOUNT ) do imp[i] := v; i := i + 1 end
    -- Add 'v' to top of stack.
  pop do i := i - 1 end
    -- Remove top of stack.
end
```

Generic Collection Class: Client (2)

As **client**, instantiate the type of `G` to be the one needed.

```
1  test_stacks: BOOLEAN
2   local
3    ss: STACK[STRING] ; sa: STACK[ACCOUNT]
4    s: STRING ; a: ACCOUNT
5   do
6    ss.push("A")
7    ss.push(create {ACCOUNT}.make ("Mark", 200))
8    s := ss.top
9    a := ss.top
10   sa.push(create {ACCOUNT}.make ("Alan", 100))
11   sa.push("B")
12   a := sa.top
13   s := sa.top
14  end
```

- **L3** commits that `ss` stores `STRING` objects only.
  - **L8** and **L10** ***valid***; **L9** and **L11** ***invalid***.
- **L4** commits that `sa` stores `ACCOUNT` objects only.
  - **L12** and **L14** ***valid***; **L13** and **L15** ***invalid***.

What are design patterns?

- Solutions to *recurring problems* that arise when software is being developed within a particular ***context***.
  - Heuristics for structuring your code so that it can be systematically maintained and extended.
  - *Caveat* : A pattern is only suitable for a particular problem.
  - Therefore, always understand *problems* before *solutions*!

Iterator Pattern: Motivation (1)

Supplier:

```
class
  CART
feature
  orders: ARRAY[ORDER]
end

class
  ORDER
feature
  price: INTEGER
  quantity: INTEGER
end
```

Problems?

Client:

```
class
  SHOP
feature
  cart: CART
  checkout: INTEGER
    do
      from
        i := cart.orders.lower
      until
        i > cart.orders.upper
      do
        Result := Result +
          cart.orders[i].price
          *
          cart.orders[i].quantity
        i := i + 1
      end
    end
end
```


Iterator Pattern: Motivation (2)

Supplier:

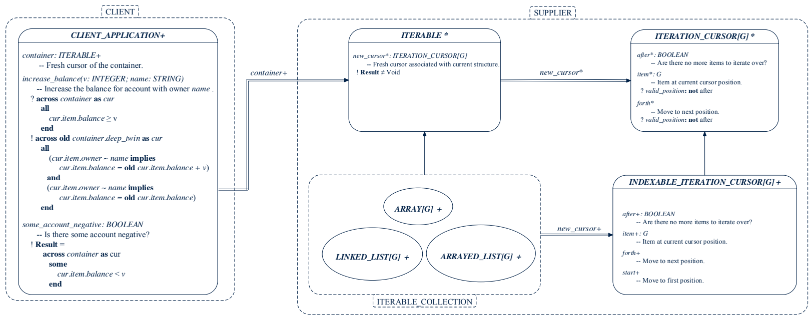
```
class
  CART
feature
  orders: LINKED_LIST[ORDER]
end

class
  ORDER
feature
  price: INTEGER
  quantity: INTEGER
end
```

Client's code must be modified to adapt to the supplier's *change on implementation*.

Client:

```
class
  SHOP
feature
  cart: CART
  checkout: INTEGER
    do
      from
        cart.orders.start
      until
        cart.orders.after
      do
        Result := Result +
          cart.orders.item.price
          *
          cart.orders.item.quantity
      end
    end
end
```

Iterator Pattern: Architecture



Iterator Pattern: Supplier's Side

- ***Information Hiding Principle*** :
  - Hide design decisions that are *likely to change* (i.e., *stable* API).
  - *Change of secrets* does not affect clients using the existing API.

    e.g., changing from *ARRAY* to *LINKED_LIST* in the *CART* class
- Steps:
  1. Let the supplier class inherit from the deferred class *ITERABLE[G]*.
  2. This forces the supplier class to implement the inherited feature: *new_cursor: ITERATION_CURSOR [G]*, where the type parameter *G* may be instantiated (e.g., *ITERATION_CURSOR[ORDER]*).
     - **2.1** If the internal, library data structure is already *iterable* e.g., *imp: ARRAY[ORDER]*, then simply return *imp.new_cursor*.
     - **2.2** Otherwise, say *imp: MY_TREE[ORDER]*, then create a new class *MY_TREE_ITERATION_CURSOR* that inherits from *ITERATION_CURSOR[ORDER]*, then implement the 3 inherited features *after*, *item*, and *forth* accordingly.

Iterator Pattern: Supplier's Implementation (1)

```
class
  CART
inherit
  ITERABLE[ORDER]

...

feature {NONE} -- Information Hiding
  orders: ARRAY[ORDER]

feature -- Iteration
  new_cursor: ITERATION_CURSOR[ORDER]
    do
      Result := orders.new_cursor
    end
```

When the secrete implementation is already *iterable*, reuse it!

Iterator Pattern: Supplier's Imp. (2.1)

```
class
  GENERIC_BOOK[G]
inherit
  ITERABLE[ TUPLE[STRING, G] ]
...
feature {NONE} -- Information Hiding
  names: ARRAY[STRING]
  records: ARRAY[G]
feature -- Iteration
  new_cursor: ITERATION_CURSOR[ TUPLE[STRING, G] ]
    local
      cursor: MY_ITERATION_CURSOR[G]
    do
      create cursor.make (names, records)
      Result := cursor
    end
```

No Eiffel library support for iterable arrays ⇒ Implement it yourself!

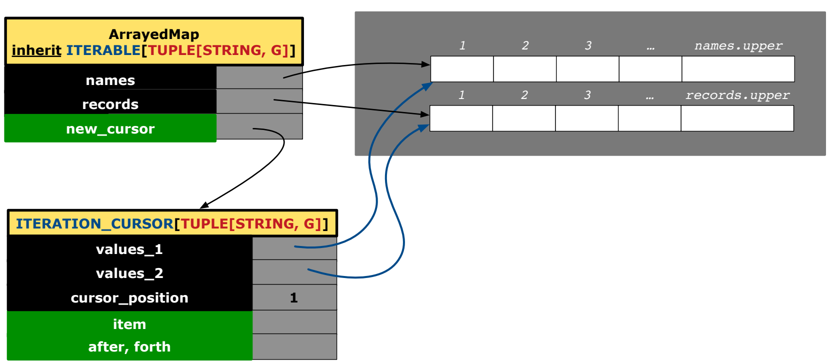
Iterator Pattern: Supplier's Imp. (2.2)

```
class
  MY_ITERATION_CURSOR[G]
inherit
  ITERATION_CURSOR[ TUPLE[STRING, G] ]
feature -- Constructor
  make (ns: ARRAY[STRING]; rs: ARRAY[G])
    do ... end
feature {NONE} -- Information Hiding
  cursor_position: INTEGER
  names: ARRAY[STRING]
  records: ARRAY[G]
feature -- Cursor Operations
  item: TUPLE[STRING, G]
    do ... end
  after: Boolean
    do ... end
  forth
    do ... end
```

You need to implement the three inherited features: *item*, *after*, and *forth*.

Iterator Pattern: Supplier's Imp. (2.3)

Visualizing iterator pattern at runtime:



Exercises

1. Draw the BON diagram showing how the iterator pattern is applied to the *CART* (supplier) and *SHOP* (client) classes.
2. Draw the BON diagram showing how the iterator pattern is applied to the supplier classes:
   - *GENERIC_BOOK* (a descendant of *ITERABLE*) and
   - *MY_ITERATION_CURSOR* (a descendant of *ITERATION_CURSOR*).

Resources

- Tutorial Videos on Generic Parameters and the Iterator Pattern
- Tutorial Videos on Information Hiding and the Iterator Pattern

Iterator Pattern: Client's Side

Information hiding : the clients do not at all depend on *how* the supplier implements the collection of data; they are only interested in iterating through the collection in a linear manner.
Steps:

1. Obey the *code to interface, not to implementation* principle.
2. Let the client declare an attribute of ***interface*** type *ITERABLE[G]* (rather than ***implementation*** type *ARRAY*, *LINKED_LIST*, or *MY_TREE*).
   e.g., `cart: CART`, where *CART* inherits `ITERATBLE[ORDER]`
3. Eiffel supports, in both implementation and *contracts*, the **across** syntax for iterating through anything that's *iterable*.

Iterator Pattern: Clients using `across` for Contracts (1)

```
class
  CHECKER
feature -- Attributes
  collection: ITERABLE [INTEGER]
feature -- Queries
  is_all_positive: BOOLEAN
      -- Are all items in collection positive?
    do
      ...
    ensure
      across
        collection as cursor
      all
        cursor.item > 0
      end
  end
```

- Using **all** corresponds to a universal quantification (i.e., ∀).
- Using **some** corresponds to an existential quantification (i.e., ∃).

Iterator Pattern: Clients using `across` for Contracts (2)

```
class BANK
...
  accounts: LIST [ACCOUNT]
  binary_search (acc_id: INTEGER): ACCOUNT
      -- Search on accounts sorted in non-descending order.
    require
      across
        1 |..| (accounts.count - 1) as cursor
      all
        accounts [cursor.item].id <= accounts [cursor.item + 1].id
      end
    do
      ...
    ensure
      Result.id = acc_id
    end
```

This precondition corresponds to:

$$\forall i : INTEGER \mid 1 \leq i < accounts.count \bullet accounts[i].id \leq accounts[i+1].id$$

Iterator Pattern: Clients using `across` for Contracts (3)

```
class BANK
...
  accounts: LIST [ACCOUNT]
  contains_duplicate: BOOLEAN
      -- Does the account list contain duplicate?
    do
      ...
    ensure
```

$$\forall i, j : INTEGER \mid 1 \leq i \leq accounts.count \wedge 1 \leq j \leq accounts.count \bullet accounts[i] \sim accounts[j] \Rightarrow i = j$$

```
    end
```

- **Exercise:** Convert this mathematical predicate for postcondition into Eiffel.
- **Hint:** Each **across** construct can only introduce one dummy variable, but you may nest as many **across** constructs as necessary.

Iterator Pattern: Clients using Iterable in Imp. (1)

```
class BANK
  accounts: ITERABLE [ACCOUNT]
  max_balance: ACCOUNT
      -- Account with the maximum balance value.
    require ??
    local
      cursor: ITERATION_CURSOR[ACCOUNT]; max: ACCOUNT
    do
      from max := accounts [1]; cursor := accounts. new_cursor
      until cursor. after
      do
        if cursor. item .balance > max.balance then
          max := cursor. item
        end
        cursor. forth
      end
    ensure ??
    end
```


Iterator Pattern: Clients using Iterable in Imp. (2)

```
1  class SHOP
2    cart: CART
3    checkout: INTEGER
4        -- Total price calculated based on orders in the cart.
5      require ??
6      local
7        order: ORDER
8      do
9        across
10         cart as cursor
11       loop
12         order := cursor. item
13         Result := Result + order.price * order.quantity
14       end
15     ensure ??
16   end
```

- Class *CART* should inherit from *ITERABLE[ORDER]*.
- **L10** implicitly declares `cursor: ITERATION_CURSOR[ORDER]` and does `cursor := cart.new_cursor`

Iterator Pattern: Clients using Iterable in Imp. (3)

```
class BANK
  accounts: ITERABLE [ACCOUNT]
  max_balance: ACCOUNT
      -- Account with the maximum balance value.
    require ??
    local
      max: ACCOUNT
    do
      max := accounts [1]
      across
        accounts as cursor
      loop
        if cursor.item.balance > max.balance then
          max := cursor. item
        end
      end
    ensure ??
    end
```


Singleton Pattern: Motivation

Consider two problems:

1. ***Bank accounts*** share a set of data.

   e.g., interest and exchange rates, minimum and maximum balance, *etc.*
2. ***Processes*** are regulated to access some shared, limited resources.

   e.g., printers

Shared Data via Inheritance

Descendant:

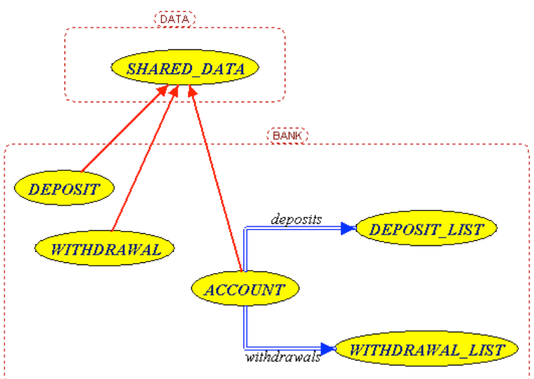
```
class DEPOSIT inherit SHARED_DATA
      -- 'maximum_balance' relevant
end

class WITHDRAW inherit SHARED_DATA
      -- 'minimum_balance' relevant
end

class INT_TRANSFER inherit SHARED_DATA
      -- 'exchange_rate' relevant
end

class ACCOUNT inherit SHARED_DATA
feature
      -- 'interest_rate' relevant
      deposits: DEPOSIT_LIST
      withdraws: WITHDRAW_LIST
end
```

Ancestor:

```
class
  SHARED_DATA
feature
  interest_rate: REAL
  exchange_rate: REAL
  minimum_balance: INTEGER
  maximum_balance: INTEGER
  ...
end
```

Problems?

Sharing Data via Inheritance: Architecture



- *Irreverent* features are inherited.
  ⇒ Descendants' *cohesion* is broken.
- Same set of data is *duplicated* as instances are created.
  ⇒ Updates on these data may result in *inconsistency*.

Sharing Data via Inheritance: Limitation

- Each descendant instance at runtime owns a separate copy of the shared data.
- This makes inheritance *not* an appropriate solution for both problems:
  - What if the interest rate changes? Apply the change to all instantiated account objects?
  - An update to the global lock must be observable by all regulated processes.

Solution:
  - Separate notions of ***data*** and its ***shared access*** in two separate classes.
  - *Encapsulate* the shared access itself in a separate class.

Introducing the Once Routine in Eiffel (1.1)

```
1  class A
2  create make
3  feature -- Constructor
4    make do end
5  feature -- Query
6    new_once_array (s: STRING): ARRAY[STRING]
7        -- A once query that returns an array.
8      once
9        create {ARRAY[STRING]} Result.make_empty
10       Result.force (s, Result.count + 1)
11     end
12   new_array (s: STRING): ARRAY[STRING]
13       -- An ordinary query that returns an array.
14     do
15       create {ARRAY[STRING]} Result.make_empty
16       Result.force (s, Result.count + 1)
17     end
18 end
```

L9 & L10 executed **only once** for initialization.
L15 & L16 executed **whenever** the feature is called.

Introducing the Once Routine in Eiffel (1.2)

```
test_query: BOOLEAN
 local
  a: A
  arr1, arr2: ARRAY[STRING]
 do
  create a.make

  arr1 := a.new_array ("Alan")
  Result := arr1.count = 1 and arr1[1] ~ "Alan"
  check Result end

  arr2 := a.new_array ("Mark")
  Result := arr2.count = 1 and arr2[1] ~ "Mark"
  check Result end

  Result := not (arr1 = arr2)
  check Result end
 end
```


Introducing the Once Routine in Eiffel (1.3)

```
test_once_query: BOOLEAN
 local
  a: A
  arr1, arr2: ARRAY[STRING]
 do
  create a.make

  arr1 := a.new_once_array ("Alan")
  Result := arr1.count = 1 and arr1[1] ~ "Alan"
  check Result end

  arr2 := a.new_once_array ("Mark")
  Result := arr2.count = 1 and arr2[1] ~ "Alan"
  check Result end

  Result := arr1 = arr2
  check Result end
end
```


Introducing the Once Routine in Eiffel (2)

```
r (...): T
    once
        -- Some computations on Result
        ...
    end
```

- The ordinary **do** ... **end** is replaced by **once** ... **end**.
- The first time the **once** routine *r* is called by some client, it executes the body of computations and returns the computed result.
- From then on, the computed result is "*cached*".
- In every subsequent call to *r*, possibly by different clients, the body of *r* is not executed at all; instead, it just returns the "*cached*" result, which was computed in the very first call.
- **How does this help us?**
  Cache the reference to the same shared object !

Approximating Once Routine in Java (1)

We may encode Eiffel once routines in Java:

```
class BankData {
  BankData() { }
  double interestRate;
  void setIR(double r);
  ...
}
```

```
class Account {
  BankData data;
  Account() {
    data = BankDataAccess.getData();
  }
}
```

```
class BankDataAccess {
  static boolean initOnce;
  static BankData data;
  static BankData getData() {
    if(!initOnce) {
      data = new BankData();
      initOnce = true;
    }
    return data;
  }
}
```

Problem?

Multiple ***BankData*** objects may be created in `Account`, breaking the singleton!

```
Account() {
  data = new BankData();
}
```

Approximating Once Routine in Java (2)

We may encode Eiffel once routines in Java:

```
class BankData {
  private BankData() { }
  double interestRate;
  void setIR(double r);
  static boolean initOnce;
  static BankData data;
  static BankData getData() {
    if(!initOnce) {
      data = new BankData();
      initOnce = true;
    }
    return data;
  }
}
```

Problem?

Loss of Cohesion: ***Data*** and ***Access to Data*** are two separate concerns, so should be decoupled into two different classes!

Singleton Pattern in Eiffel (1)

Supplier:

```
class DATA
create {DATA_ACCESS} make
feature {DATA_ACCESS}
  make do v := 10 end
feature -- Data Attributes
  v: INTEGER
  change_v (nv: INTEGER)
    do v := nv end
end
```

```
expanded class
  DATA_ACCESS
feature
  data: DATA
      -- The one and only access
    once create Result.make end
invariant data = data
```

Client:

```
test: BOOLEAN
  local
    access: DATA_ACCESS
    d1, d2: DATA
  do
    d1 := access.data
    d2 := access.data
    Result := d1 = d2
      and d1.v = 10 and d2.v = 10
    check Result end
    d1.change_v (15)
    Result := d1 = d2
      and d1.v = 15 and d2.v = 15
  end
end
```

Writing **create *d1.make*** in `test` feature does not compile. Why?

Singleton Pattern in Eiffel (2)

Supplier:

```
class BANK_DATA
create {BANK_DATA_ACCESS} make
feature {BANK_DATA_ACCESS}
  make do ... end
feature -- Data Attributes
  interest_rate: REAL
  set_interest_rate (r: REAL)
  ...
end
```

```
expanded class
  BANK_DATA_ACCESS
feature
  data: BANK_DATA
      -- The one and only access
    once create Result.make end
invariant data = data
```

Client:

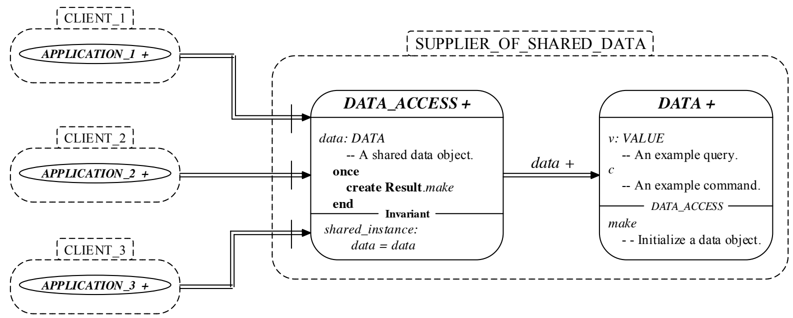
```
class
  ACCOUNT
feature
  data: BANK_DATA
  make (...)
      -- Init. access to bank data.
    local
      data_access: BANK_DATA_ACCESS
    do
      data := data_access.data
      ...
    end
end
```

Writing **create *data.make*** in client's `make` feature does not compile. Why?

Testing Singleton Pattern in Eiffel

```
test_bank_shared_data: BOOLEAN
    -- Test that a single data object is manipulated
  local acc1, acc2: ACCOUNT
  do
    comment("t1: test that a single data object is shared")
    create acc1.make ("Bill")
    create acc2.make ("Steve")
    Result := acc1.data = acc2.data
    check Result end
    Result := acc1.data ~ acc2.data
    check Result end
    acc1.data.set_interest_rate (3.11)
    Result :=
          acc1.data.interest_rate = acc2.data.interest_rate
      and acc1.data.interest_rate = 3.11
    check Result end
    acc2.data.set_interest_rate (2.98)
    Result :=
          acc1.data.interest_rate = acc2.data.interest_rate
      and acc1.data.interest_rate = 2.98
  end
```

Singleton Pattern: Architecture



Important Exercises: Instantiate this architecture to both problems of shared bank data and shared lock. Draw them in `draw.io`.

Index (1)

Index (2)

Index (3)

Index (4)

Aspects of Inheritance

- ***Code Reuse***
- Substitutability
  - ***Polymorphism*** and ***Dynamic Binding***
    [compile-time type checks]
  - *Sub-contracting*
    [runtime behaviour checks]

Inheritance

Readings: OOSCS2 Chapters 14 – 16

YORK UNIVERSITÉ UNIVERSITY

EECS3311 M: Software Design
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CHEN-WEI WANG

Why Inheritance: A Motivating Example

Problem: A *student management system* stores data about students. There are two kinds of university students: *resident* students and *non-resident* students. Both kinds of students have a *name* and a list of *registered courses*. Both kinds of students are restricted to *register* for no more than 30 courses. When *calculating the tuition* for a student, a base amount is first determined from the list of courses they are currently registered (each course has an associated fee). For a non-resident student, there is a *discount rate* applied to the base amount to waive the fee for on-campus accommodation. For a resident student, there is a *premium rate* applied to the base amount to account for the fee for on-campus accommodation and meals.

Tasks: Design classes that satisfy the above problem statement. At runtime, each type of student must be able to register a course and calculate their tuition fee.

The COURSE Class

```
class
  COURSE

create -- Declare commands that can be used as constructors
  make

feature -- Attributes
  title: STRING
  fee: REAL

feature -- Commands
  make (t: STRING; f: REAL)
      -- Initialize a course with title 't' and fee 'f'.
    do
      title := t
      fee := f
    end
end
```


No Inheritance: RESIDENT_STUDENT Class

```
class RESIDENT_STUDENT
create make
feature -- Attributes
  name: STRING
  courses: LINKED_LIST[COURSE]
  premium_rate: REAL
feature -- Constructor
  make (n: STRING)
    do name := n ; create courses.make end
feature -- Commands
  set_pr (r: REAL) do premium_rate := r end
  register (c: COURSE) do courses.extend (c) end
feature -- Queries
  tuition: REAL
    local base: REAL
    do base := 0.0
       across courses as c loop base := base + c.item.fee end
       Result := base * premium_rate
    end
end
```


No Inheritance: NON_RESIDENT_STUDENT Class

```
class NON_RESIDENT_STUDENT
create make
feature -- Attributes
  name: STRING
  courses: LINKED_LIST[COURSE]
  discount_rate: REAL
feature -- Constructor
  make (n: STRING)
    do name := n ; create courses.make end
feature -- Commands
  set_dr (r: REAL) do discount_rate := r end
  register (c: COURSE) do courses.extend (c) end
feature -- Queries
  tuition: REAL
    local base: REAL
    do base := 0.0
       across courses as c loop base := base + c.item.fee end
       Result := base * discount_rate
    end
end
```


No Inheritance: Testing Student Classes

```
test_students: BOOLEAN
  local
    c1, c2: COURSE
    jim: RESIDENT_STUDENT
    jeremy: NON_RESIDENT_STUDENT
  do
    create c1.make ("EECS2030", 500.0)
    create c2.make ("EECS3311", 500.0)
    create jim.make ("J. Davis")
    jim.set_pr (1.25)
    jim.register (c1)
    jim.register (c2)
    Result := jim.tuition = 1250
    check Result end
    create jeremy.make ("J. Gibbons")
    jeremy.set_dr (0.75)
    jeremy.register (c1)
    jeremy.register (c2)
    Result := jeremy.tuition = 750
  end
```

No Inheritance: Issues with the Student Classes

- Implementations for the two student classes seem to work. But can you see any potential problems with it?
- The code of the two student classes share a lot in common.
- *Duplicates of code make it hard to maintain your software!*
- This means that when there is a change of policy on the common part, we need modify *more than one places*.

  ⇒ This violates the *Single Choice Principle* :

  when a ***change*** is needed, there should be ***a single place*** (or ***a minimal number of places***) where you need to make that change.

No Inheritance: Maintainability of Code (1)

What if a ***new*** way for course registration is to be implemented?

e.g.,

```
register(Course c)
 do
  if courses.count >= MAX_CAPACITY then
   -- Error: maximum capacity reached.
  else
   courses.extend (c)
  end
 end
```

We need to change the `register` commands in ***both*** student classes!

⇒ ***Violation*** of the *Single Choice Principle*

No Inheritance: Maintainability of Code (2)

What if a ***new*** way for base tuition calculation is to be implemented?

e.g.,

```
tuition: REAL
  local base: REAL
 do base := 0.0
    across courses as c loop base := base + c.item.fee end
    Result := base * inflation_rate * ...
 end
```

We need to change the `tuition` query in ***both*** student classes.

⇒ ***Violation*** of the *Single Choice Principle*

No Inheritance: A Collection of Various Kinds of Students

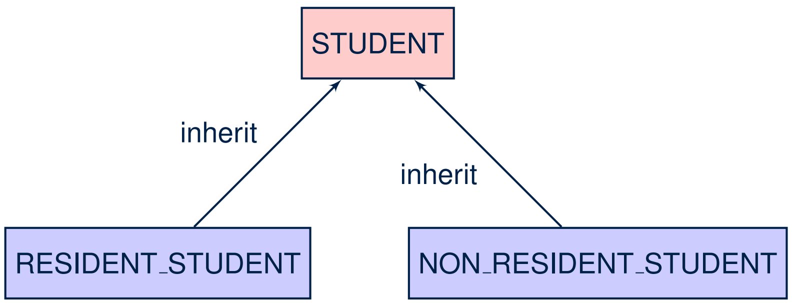
How do you define a class `StudentManagementSystem` that contains a list of *resident* and *non-resident* students?

```
class STUDENT_MANAGEMENT_SYSETM
  rs : LINKED_LIST[RESIDENT_STUDENT]
  nrs : LINKED_LIST[NON_RESIDENT_STUDENT]
  add_rs (rs: RESIDENT_STUDENT) do ... end
  add_nrs (nrs: NON_RESIDENT_STUDENT) do ... end
  register_all (Course c) -- Register a common course 'c'.
    do
      across rs as c loop c.item.register (c) end
      across nrs as c loop c.item.register (c) end
    end
end
```

But what if we later on introduce *more kinds of students*?

Inconvenient to handle each list of students, in pretty much the ***same*** manner, *separately*!

Inheritance Architecture



Inheritance: The STUDENT Parent Class

```
class STUDENT
create make
feature -- Attributes
  name: STRING
  courses: LINKED_LIST[COURSE]
feature -- Commands that can be used as constructors.
  make (n: STRING) do name := n ; create courses.make end
feature -- Commands
  register (c: COURSE) do courses.extend (c) end
feature -- Queries
  tuition: REAL
    local base: REAL
    do base := 0.0
       across courses as c loop base := base + c.item.fee end
       Result := base
    end
end
```


Inheritance: The RESIDENT_STUDENT Child Class

```
1  class
2   RESIDENT_STUDENT
3  inherit
4   STUDENT
5    redefine tuition end
6  create make
7  feature -- Attributes
8   premium_rate : REAL
9  feature -- Commands
10  set_pr (r: REAL) do premium_rate := r end
11 feature -- Queries
12  tuition: REAL
13   local base: REAL
14   do base := Precursor ;  Result := base * premium_rate end
15 end
```

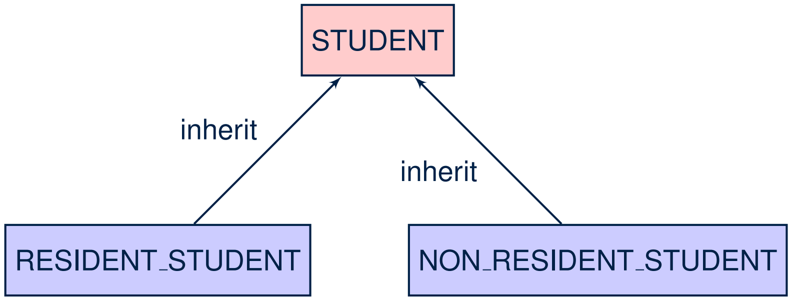
- **L3**: RESIDENT_STUDENT inherits all features from STUDENT.
- There is no need to repeat the register command
- **L14**: *Precursor* returns the value from query tuition in STUDENT.

Inheritance: The NON_RESIDENT_STUDENT Child Class

```
1  class
2   NON_RESIDENT_STUDENT
3  inherit
4   STUDENT
5    redefine tuition end
6  create make
7  feature -- Attributes
8   discount_rate : REAL
9  feature -- Commands
10  set_dr (r: REAL) do discount_rate := r end
11 feature -- Queries
12  tuition: REAL
13   local base: REAL
14   do base := Precursor ;  Result := base * discount_rate end
15 end
```

- **L3**: NON_RESIDENT_STUDENT inherits all features from STUDENT.
- There is no need to repeat the register command
- **L14**: *Precursor* returns the value from query tuition in STUDENT.

Inheritance Architecture Revisited



- The class that defines the common features (attributes, commands, queries) is called the *parent*, *super*, or *ancestor* class.
- Each "specialized" class is called a *child*, *sub*, or *descendent* class.

Using Inheritance for Code Reuse

Inheritance in Eiffel (or any OOP language) allows you to:

- Factor out *common features* (attributes, commands, queries) in a separate class.
  e.g., the `STUDENT` class
- Define an "specialized" version of the class which:
  - *inherits* definitions of all attributes, commands, and queries
    e.g., attributes `name`, `courses`
    e.g., command `register`
    e.g., query on base amount in `tuition`
    This means code reuse and elimination of code duplicates!
  - *defines* **new** features if necessary
    e.g., `set_pr` for `RESIDENT_STUDENT`
    e.g., `set_dr` for `NON_RESIDENT_STUDENT`
  - *redefines* features if necessary
    e.g., compounded tuition for `RESIDENT_STUDENT`
    e.g., discounted tuition for `NON_RESIDENT_STUDENT`

Testing the Two Student Sub-Classes

```
test_students: BOOLEAN
 local
  c1, c2: COURSE
  jim: RESIDENT_STUDENT ; jeremy: NON_RESIDENT_STUDENT
 do
  create c1.make ("EECS2030", 500.0); create c2.make ("EECS3311", 500.0)
  create jim.make ("J. Davis")
  jim.set_pr (1.25) ; jim.register (c1); jim.register (c2)
  Result := jim.tuition = 1250
  check Result end
  create jeremy.make ("J. Gibbons")
  jeremy.set_dr (0.75); jeremy.register (c1); jeremy.register (c2)
  Result := jeremy.tuition = 750
 end
```

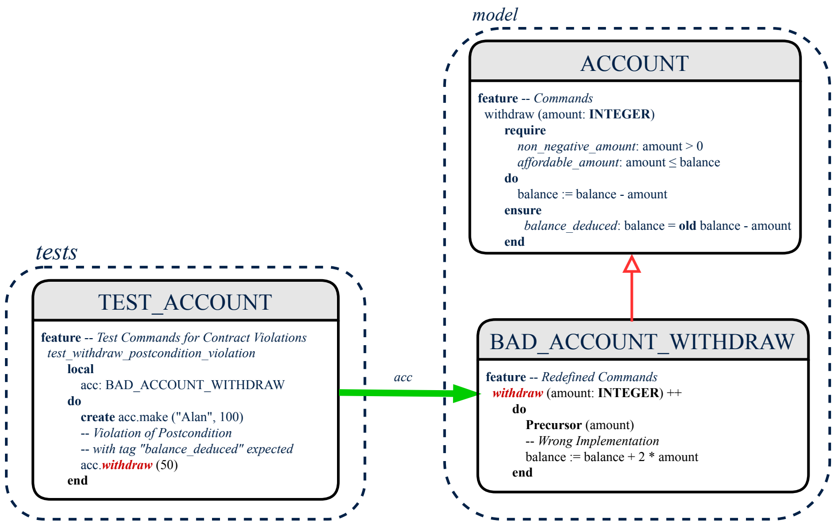
- The software can be used in exactly the same way as before (because we did not modify *feature signatures*).
- But now the internal structure of code has been made *maintainable* using *inheritance*.

DbC: Contract View of Supplier

Any potential **client** who is interested in learning about the kind of services provided by a **supplier** can look through the *contract view* (without showing any implementation details):

```
class ACCOUNT
create
      make
feature -- Attributes
      owner : STRING
      balance : INTEGER
feature -- Constructors
      make(nn: STRING; nb: INTEGER)
            require -- precondition
                  positive_balance: nb > 0
            end
feature -- Commands
      withdraw(amount: INTEGER)
            require -- precondition
                  non_negative_amount: amount > 0
                  affordable_amount: amount <= balance -- problematic, why?
            ensure -- postcondition
                  balance_deducted: balance = old balance - amount
            end
invariant -- class invariant
      positive_balance: balance > 0
end
```

ES_TEST: Expecting to Fail Postcondition (1)



ES_TEST: Expecting to Fail Postcondition (2.1)

```
1  class
2    BAD_ACCOUNT_WITHDRAW
3  inherit
4    ACCOUNT
5      redefine withdraw end
6  create
7    make
8  feature -- redefined commands
9    withdraw(amount: INTEGER)
10     do
11       Precursor(amount)
12       -- Wrong implementation
13       balance := balance + 2 * amount
14     end
15 end
```

- **L3–5**: BAD_ACCOUNT_WITHDRAW.withdraw inherits postcondition from ACCOUNT.withdraw: balance = **old** balance - amount.
- **L11** calls *correct* implementation from parent class ACCOUNT.
- **L13** makes overall implementation *incorrect*.

ES_TEST: Expecting to Fail Postcondition (2.2)

```
class TEST_ACCOUNT
inherit ES_TEST
create make
feature -- Constructor for adding tests
  make
    do
      add_violation_case_with_tag ("balance_deducted",
        agent test_withdraw_postcondition_violation)
    end
feature -- Test commands (test to fail)
  test_withdraw_postcondition_violation
    local
      acc: BAD_ACCOUNT_WITHDRAW
    do
      comment ("test: expected postcondition violation of withdraw")
      create acc.make ("Alan", 100)
      -- Postcondition Violation with tag "balance_deduced" to occur.
      acc.withdraw (50)
    end
end
```


Exercise

Recall from the "Writing Complete Postconditions" lecture:

```
class BANK
  deposit_on_v5 (n: STRING; a: INTEGER)
    do ... -- Put Correct Implementation Here.
    ensure
      ...
      others_unchanged :
        across old accounts.deep_twin as cursor
        all cursor.item.owner /~ n implies
            cursor.item ~ account_of (cursor.item.owner)
        end
    end
end
```

How do you create a "bad" descendant of BANK that violates this postcondition?

```
class BAD_BANK_DEPOSIT
inherit BANK redefine deposit end
feature -- redefined feature
  deposit_on_v5 (n: STRING; a: INTEGER)
    do Precursor (n, a)
        accounts[accounts.lower].deposit(a)
    end
end
```

Static Type vs. Dynamic Type

- In *object orientation*, an entity has two kinds of types:
  - *static type* is declared at compile time [**unchangeable**]
    An entity's ***ST*** determines what features may be called upon it.
  - *dynamic type* is changeable at runtime
- In Java:

```
Student s = new Student("Alan");
Student rs = new ResidentStudent("Mark");
```

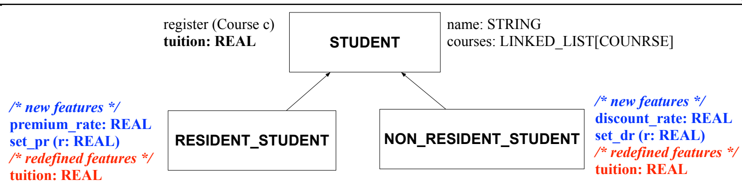
- In Eiffel:

```
local s: STUDENT
      rs: STUDENT
do create {STUDENT} s.make ("Alan")
   create {RESIDENT_STUDENT} rs.make ("Mark")
```

  - In Eiffel, the *dynamic type* can be omitted if it is meant to be the same as the *static type*:

```
local s: STUDENT
do create s.make ("Alan")
```


Inheritance Architecture Revisited




```
s1,s2,s3: STUDENT ; rs: RESIDENT_STUDENT ; nrs : NON_RESIDENT_STUDENT
create {STUDENT} s1.make ("S1")
create {RESIDENT_STUDENT} s2.make ("S2")
create {NON_RESIDENT_STUDENT} s3.make ("S3")
create {RESIDENT_STUDENT} rs.make ("RS")
create {NON_RESIDENT_STUDENT} nrs.make ("NRS")
```

	name	courses	reg	tuition	pr	set_pr	dr	set_dr
s1.	✓				×			
s2.	✓				×			
s3.	✓				×			
rs.	✓				✓		×	
nrs.	✓				×		✓	

Polymorphism: Intuition (1)

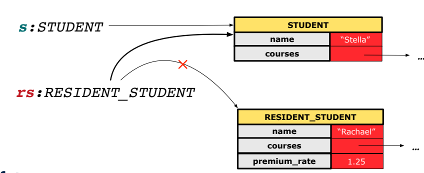
```
1 local
2   s: STUDENT
3   rs: RESIDENT_STUDENT
4 do
5   create s.make ("Stella")
6   create rs.make ("Rachael")
7   rs.set_pr (1.25)
8   s := rs /* Is this valid? */
9   rs := s /* Is this valid? */
```

- Which one of **L8** and **L9** is *valid*? Which one is *invalid*?
  - **L8**: What *kind* of address can ***s*** store? [STUDENT]
    ∴ The context object ***s*** is *expected* to be used as:
    - ***s***.register(eecs3311) and ***s***.tuition
  - **L9**: What *kind* of address can ***rs*** store? [RESIDENT_STUDENT]
    ∴ The context object ***rs*** is *expected* to be used as:
    - ***rs***.register(eecs3311) and ***rs***.tuition
    - ***rs***.*set_pr (1.50)* [increase premium rate]

Polymorphism: Intuition (2)

```
1 local s: STUDENT ; rs: RESIDENT_STUDENT
2 do create {STUDENT} s.make ("Stella")
3    create {RESIDENT_STUDENT} rs.make ("Rachael")
4    rs.set_pr (1.25)
5    s := rs /* Is this valid? */
6    rs := s /* Is this valid? */
```

- ***rs*** := ***s*** (**L6**) should be *invalid*:

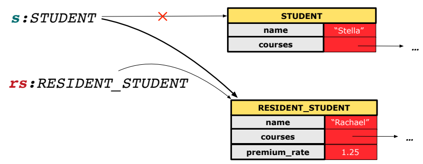


- ***rs*** declared of type RESIDENT_STUDENT
  ∴ calling ***rs***.*set_pr(1.50)* can be expected.
- ***rs*** is now pointing to a STUDENT object.
- Then, what would happen to ***rs***.*set_pr(1.50)*?
  CRASH ∵ ***rs***.premium_rate is *undefined*!!

Polymorphism: Intuition (3)

```
1  local s: STUDENT ; rs: RESIDENT_STUDENT
2  do create {STUDENT} s.make ("Stella")
3     create {RESIDENT_STUDENT} rs.make ("Rachael")
4     rs.set_pr (1.25)
5     s := rs /* Is this valid? */
6     rs := s /* Is this valid? */
```

- *s* := *rs* (**L5**) should be *valid*:



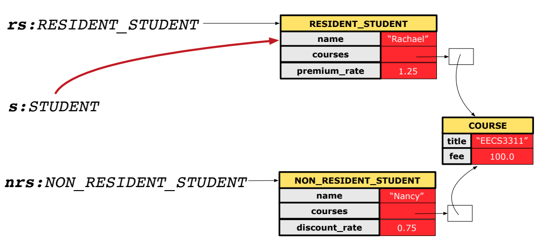
- Since *s* is declared of type `STUDENT`, a subsequent call *s.set_pr(1.50)* is *never* expected.
- *s* is now pointing to a `RESIDENT_STUDENT` object.
- Then, what would happen to *s.tuition*?

OK ∵ *s*.`premium_rate` is just *never used*!!

Dynamic Binding: Intuition (1)

```
1  local c : COURSE ; s : STUDENT
2  do crate c.make ("EECS3311", 100.0)
3     create {RESIDENT_STUDENT} rs.make("Rachael")
4     create {NON_RESIDENT_STUDENT} nrs.make("Nancy")
5     rs.set_pr(1.25); rs.register(c)
6     nrs.set_dr(0.75); nrs.register(c)
7     s := rs; ; check s.tuition = 125.0 end
8     s := nrs; ; check s.tuition = 75.0 end
```

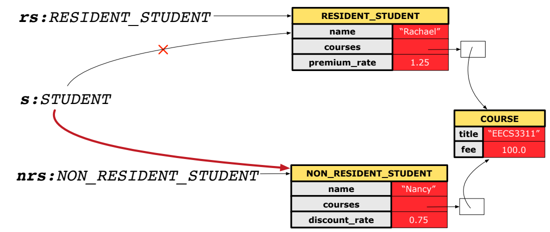
After `s := rs` (**L7**), `s` points to a `RESIDENT_STUDENT` object.
⇒ Calling `s.tuition` applies the `premium_rate`.



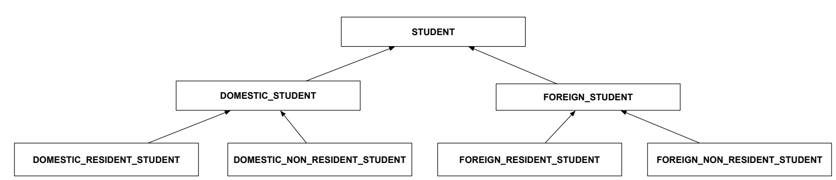
Dynamic Binding: Intuition (2)

```
1  local c : COURSE ; s : STUDENT
2  do crate c.make ("EECS3311", 100.0)
3     create {RESIDENT_STUDENT} rs.make("Rachael")
4     create {NON_RESIDENT_STUDENT} nrs.make("Nancy")
5     rs.set_pr(1.25); rs.register(c)
6     nrs.set_dr(0.75); nrs.register(c)
7     s := rs; ; check s.tuition = 125.0 end
8     s := nrs; ; check s.tuition = 75.0 end
```

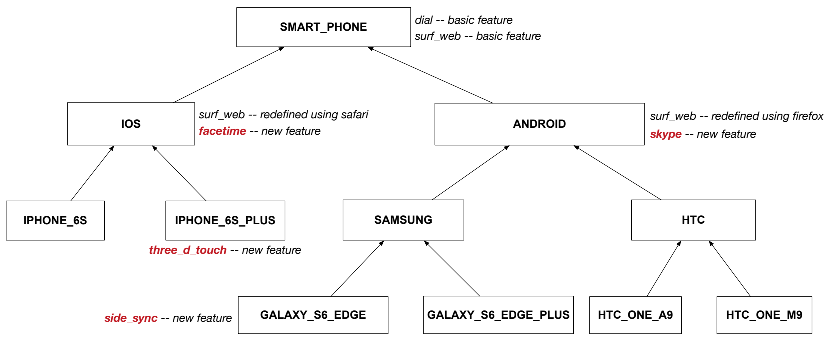
After `s:=nrs` (**L8**), `s` points to a `NON_RESIDENT_STUDENT` object.
⇒ Calling `s.tuition` applies the `discount_rate`.



Multi-Level Inheritance Architecture (1)



Multi-Level Inheritance Architecture (2)



Inheritance Forms a Type Hierarchy

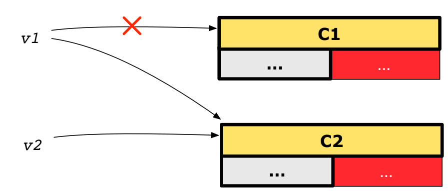
- A (data) *type* denotes a set of related *runtime values*.
  - Every *class* can be used as a type: the set of runtime *objects*.
- Use of *inheritance* creates a *hierarchy* of classes:
  - (Implicit) Root of the hierarchy is `ANY`.
  - Each `inherit` declaration corresponds to an upward arrow.
  - The `inherit` relationship is *transitive*: when `A` inherits `B` and `B` inherits C, we say `A` *indirectly* inherits `C`.
    e.g., Every class implicitly `inherits` the `ANY` class.
- *Ancestor* vs. *Descendant* classes:
  - The *ancestor classes* of a class `A` are: `A` itself and all classes that `A` directly, or indirectly, inherits.
    - `A` inherits all features from its *ancestor classes*.
      ∴ `A`'s instances have a ***wider range of expected usages*** (i.e., attributes, queries, commands) than instances of its *ancestor* classes.
  - The *descendant classes* of a class `A` are: `A` itself and all classes that directly, or indirectly, inherits `A`.
    - Code defined in `A` is inherited to all its *descendant classes*.

Inheritance Accumulates Code for Reuse

- The *lower* a class is in the type hierarchy, the *more code* it accumulates from its *ancestor classes*:
  - A *descendant class* inherits all code from its *ancestor classes*.
  - A *descendant class* may also:
    - Declare new attributes.
    - Define new queries or commands.
    - *Redefine* inherited queries or commands.
- Consequently:
  - When being used as *context objects*, instances of a class' *descendant classes* have a ***wider range of expected usages*** (i.e., attributes, commands, queries).
  - When expecting an object of a particular class, we may *substitute* it with an object of any of its *descendant classes*.
  - e.g., When expecting a `STUDENT` object, substitute it with either a `RESIDENT_STUDENT` or a `NON_RESIDENT_STUDENT` object.
  - **Justification**: A *descendant class* contains *at least as many* features as defined in its *ancestor classes* (but ***not vice versa***!).

Substitutions via Assignments

- By declaring `v1:C1`, *reference variable* `v1` will store the *address* of an object of class `C1` at runtime.
- By declaring `v2:C2`, *reference variable* `v2` will store the *address* of an object of class `C2` at runtime.
- Assignment `v1:=v2` *copies the address* stored in `v2` into `v1`.
  - `v1` will instead point to wherever `v2` is pointing to. [*object alias*]



- In such assignment `v1:=v2`, we say that we *substitute* an object of type `C1` with an object of type `C2`.
- *Substitutions* are subject to *rules*!

Rules of Substitution

Given an inheritance hierarchy:

1. When expecting an object of class `A`, it is *safe* to **substitute** it with an object of any **descendant class** of `A` (including `A`).
   - e.g., When expecting an `IOS` phone, you *can* substitute it with either an `IPhone6s` or `IPhone6sPlus`.
   - ∵ Each **descendant class** of `A` is guaranteed to contain all code of (non-private) attributes, commands, and queries defined in `A`.
   - ∴ All features defined in `A` are *guaranteed to be available* in the new substitute.
2. When expecting an object of class `A`, it is *unsafe* to **substitute** it with an object of any **ancestor class of `A`'s parent**.
   - e.g., When expecting an `IOS` phone, you *cannot* substitute it with just a `SmartPhone`, because the `facetime` feature is not supported in an `Android` phone.
   - ∵ Class `A` may have defined new features that do not exist in any of its **parent's ancestor classes**.

Reference Variable: Static Type

- A *reference variable*'s **static type** is what we declare it to be.
  - e.g., `jim:STUDENT` declares `jim`'s static type as `STUDENT`.
  - e.g., `my_phone:SMART_PHONE` declares a variable `my_phone` of static type `SmartPhone`.
  - The **static type** of a *reference variable never changes*.
- For a *reference variable* v, its **static type** C defines the **expected usages of v as a context object**.
- A feature call `v.m(...)` is ***compilable*** if ***m*** is defined in C.
  - e.g., After declaring `jim:STUDENT`, we
    - **may** call `register` and `tuition` on `jim`
    - **may *not*** call `set_pr` (specific to a resident student) or `set_dr` (specific to a non-resident student) on `jim`
  - e.g., After declaring `my_phone:SMART_PHONE`, we
    - **may** call `dial` and `surf_web` on `my_phone`
    - **may *not*** call `facetime` (specific to an IOS phone) or `skype` (specific to an Android phone) on `my_phone`

Reference Variable: Dynamic Type

A *reference variable*'s **dynamic type** is the type of object that it is currently pointing to at runtime.

- The *dynamic type* of a reference variable *may change* whenever we **re-assign** that variable to a different object.
- There are two ways to re-assigning a reference variable.

Reference Variable: Changing Dynamic Type (1)

Re-assigning a reference variable to a newly-created object:

- **Substitution Principle**: the new object's class must be a *descendant class* of the reference variable's *static type*.
- e.g., Given the declaration `jim:STUDENT`:
  - `create {RESIDENT_STUDENT} jim.make ("Jim")` changes the *dynamic type* of `jim` to `RESIDENT_STUDENT`.
  - `create {NON_RESIDENT_STUDENT} jim.make ("Jim")` changes the *dynamic type* of `jim` to `NON_RESIDENT_STUDENT`.
- e.g., Given an alternative declaration `jim:RESIDENT_STUDENT`:
  - e.g., `create {STUDENT} jim.make ("Jim")` is illegal because `STUDENT` is not a *descendant class* of the *static type* of `jim` (i.e., `RESIDENT_STUDENT`).

Reference Variable: Changing Dynamic Type (2)

Re-assigning a reference variable `v` to an existing object that is referenced by another variable `other` (i.e., `v := other`):

- *Substitution Principle*: the static type of `other` must be a *descendant class* of `v`'s *static type*.
- e.g.,

```
jim: STUDENT ; rs: RESIDENT_STUDENT; nrs: NON_RESIDENT_STUDENT
create {STUDENT} jim.make (...)
create {RESIDENT_STUDENT} rs.make (...)
create {NON_RESIDENT_STUDENT} nrs.make (...)
```

  - `rs := jim` ×
  - `nrs := jim` ×
  - `jim := rs` ✓
    changes the *dynamic type* of `jim` to the dynamic type of `rs`
  - `jim := nrs` ✓
    changes the *dynamic type* of `jim` to the dynamic type of `nrs`

Polymorphism and Dynamic Binding (1)

- *Polymorphism*: An object variable may have *"multiple possible shapes"* (i.e., allowable *dynamic types*).
  - Consequently, there are *multiple possible versions* of each feature that may be called.
    - e.g., 3 possibilities of `tuition` on a ***STUDENT*** reference variable:
      In ***STUDENT***: base amount
      In ***RESIDENT_STUDENT***: base amount with `premium_rate`
      In ***NON_RESIDENT_STUDENT***: base amount with `discount_rate`
- *Dynamic binding*: When a feature `m` is called on an object variable, the version of `m` corresponding to its *"current shape"* (i.e., one defined in the *dynamic type* of *m*) will be called.

```
jim: STUDENT; rs: RESIDENT_STUDENT; nrs: NON_STUDENT
create {RESIDENT_STUDENT} rs.make (...)
create {NON_RESIDENT_STUDENT} nrs.nrs (...)
jim := rs
jim.tuitoion;  /* version in RESIDENT_STUDENT */
jim := nrs
jim.tuition;  /* version in NON_RESIDENT_STUDENT */
```


Polymorphism and Dynamic Binding (2.1)

```
1  test_polymorphism_students
2   local
3     jim: STUDENT
4     rs: RESIDENT_STUDENT
5     nrs: NON_RESIDENT_STUDENT
6   do
7     create {STUDENT} jim.make ("J. Davis")
8     create {RESIDENT_STUDENT} rs.make ("J. Davis")
9     create {NON_RESIDENT_STUDENT} nrs.make ("J. Davis")
10    jim := rs  ✓
11    rs := jim  ×
12    jim := nrs  ✓
13    rs := jim  ×
14  end
```

In (**L3**, **L7**), (**L4**, **L8**), (**L5**, **L9**), ***ST*** = ***DT***, so we may abbreviate:

L7: `create jim.make ("J. Davis")`

L8: `create rs.make ("J. Davis")`

L9: `create nrs.make ("J. Davis")`

Polymorphism and Dynamic Binding (2.2)

```
test_dynamic_binding_students: BOOLEAN
 local
   jim: STUDENT
   rs: RESIDENT_STUDENT
   nrs: NON_RESIDENT_STUDENT
   c: COURSE
 do
   create c.make ("EECS3311", 500.0)
   create {STUDENT} jim.make ("J. Davis")
   create {RESIDENT_STUDENT} rs.make ("J. Davis")
   rs.register (c)
   rs.set_pr (1.5)
   jim := rs
   Result := jim.tuition = 750.0
   check Result end
   create {NON_RESIDENT_STUDENT} nrs.make ("J. Davis")
   nrs.register (c)
   nrs.set_dr (0.5)
   jim := nrs
   Result := jim.tuition = 250.0
end
```

Reference Type Casting: Motivation

```
1 local jim: STUDENT; rs: RESIDENT_STUDENT
2 do create {RESIDENT_STUDENT} jim.make ("J. Davis")
3   rs := jim
4   rs.setPremiumRate(1.5)
```

- **Line 2** is *legal*: RESIDENT_STUDENT is a *descendant class* of the static type of `jim` (i.e., STUDENT).
- **Line 3** is *illegal*: `jim`'s static type (i.e., STUDENT) is ***not*** a *descendant class* of `rs`'s static type (i.e., RESIDENT_STUDENT).
- Eiffel compiler is *unable to infer* that `jim`'s *dynamic type* in **Line 4** is RESIDENT_STUDENT. [*Undecidable*]
- Force the Eiffel compiler to believe so, by replacing **L3**, **L4** by a *type cast* (which *temporarily* changes the ***ST*** of `jim`):

```
check attached {RESIDENT_STUDENT} jim as rs_jim then
  rs := rs_jim
  rs.set_pr (1.5)
end
```


Reference Type Casting: Syntax

```
1 check attached {RESIDENT_STUDENT} jim as rs_jim then
2   rs := rs_jim
3   rs.set_pr (1.5)
4 end
```

L1 is an assertion:
- `attached RESIDENT_STUDENT jim` is a Boolean expression that is to be evaluated at ***runtime***.
  - If it evaluates to ***true***, then the `as rs_jim` expression has the effect of assigning "the cast version" of `jim` to a new variable `rs_jim`.
  - If it evaluates to ***false***, then a runtime assertion violation occurs.
- *Dynamic Binding*: **Line 4** executes the correct version of `set_pr`.

- It is equivalent to the following Java code:

```
if(jim instanceof ResidentStudent) {
  ResidentStudent rs = (ResidentStudent) jim;
  rs.set_pr(1.5);
}
else { throw new Exception("Cast Not Done."); }
```


Notes on Type Cast (1)

- Given *v* of static type *ST*, it is ***compilable*** to cast *v* to *C*, as long as *C* is a descendant or ancestor class of *ST*.
- Why Cast?
  - Without cast, we can **only** call features defined in *ST* on *v*.
  - By casting *v* to *C*, we *change* the *static type* of *v* from *ST* to *C*.

    ⇒ All features that are defined in *C* can be called.

```
my_phone: IOS
create {IPHONE_6S_PLUS} my_phone.make
-- can only call features defined in IOS on myPhone
-- dial, surf_web, facetime ✓   three_d_touch, skype ×
check attached {SMART_PHONE} my_phone as sp then
  -- can now call features defined in SMART_PHONE on sp
  -- dial, surf_web ✓   facetime, three_d_touch, skype ×
end
check attached {IPHONE_6S_PLUS} my_phone as ip6s_plus then
  -- can now call features defined in IPHONE_6S_PLUS on ip6s_plus
  -- dial, surf_web, facetime, three_d_touch ✓   skype ×
end
```


Notes on Type Cast (2)

- A cast being ***compilable*** is not necessarily ***runtime-error-free***!
- A cast `check attached {C} v as ...` triggers an assertion violation if `C` is ***not*** along the **ancestor path** of `v`'s *DT*.

```
test_smart_phone_type_cast_violation
  local mine: ANDROID
  do create {SAMSUNG} mine.make
    -- ST of mine is ANDROID; DT of mine is SAMSUNG
    check attached {SMART_PHONE} mine as sp then ... end
    -- ST of sp is SMART_PHONE; DT of sp is SAMSUNG
    check attached {SAMSUNG} mine as samsung then ... end
    -- ST of samsung is SAMSNG; DT of samsung is SAMSUNG
    check attached {HTC} mine as htc then ... end
    -- Compiles ∵ HTC is descendant of mine's ST (ANDROID)
    -- Assertion violation
    -- ∵ HTC is not ancestor of mine's DT (SAMSUNG)
    check attached {GALAXY_S6_EDGE} mine as galaxy then ... end
    -- Compiles ∵ GALAXY_S6_EDGE is descendant of mine's ST (ANDROID)
    -- Assertion violation
    -- ∵ GALAXY_S6_EDGE is not ancestor of mine's DT (SAMSUNG)
end
```

Compilable Cast vs. Exception-Free Cast (1)

```
class A end
class B inherit A end
class C inherit B end
class D inherit A end
```

```
1 local b: B ; d: D
2 do
3   create {C} b.make
4   check attached {D} b as temp then d := temp end
5 end
```

- After **L3**: b's ***ST*** is B and b's ***DT*** is C.
- Does **L4** compile? [NO]

  ∵ cast type D is neither an ancestor nor a descendant of b's ***ST*** B

Compilable Cast vs. Exception-Free Cast (2)

```
class A end
class B inherit A end
class C inherit B end
class D inherit A end
```

```
1 local b: B ; d: D
2 do
3   create {C} b.make
4   check attached {D} b as temp then d := temp end
5 end
```

- Would the following fix **L4**?

```
check attached {A} b as temp1 then
  check attached {D} temp1 as temp2 then d := temp2 end
end
```

  YES ∵ cast type D is an ancestor of b's cast, temporary ***ST*** A
- What happens when executing this fix?

  Assertion Violation ∵ cast type D not an ancestor of temp1's ***DT*** C

Polymorphism: Feature Call Arguments (1)

```
1 class STUDENT_MANAGEMENT_SYSTEM {
2   ss : ARRAY[STUDENT] -- ss[i] has static type Student
3   add_s (s: STUDENT) do ss[0] := s end
4   add_rs (rs: RESIDENT_STUDENT) do ss[0] := rs end
5   add_nrs (nrs: NON_RESIDENT_STUDENT) do ss[0] := nrs end
```

- **L4**: `ss[0]:=rs` is valid. ∵ RHS's ST ***RESIDENT_STUDENT*** is a *descendant class* of LHS's ST ***STUDENT***.
- Say we have a STUDENT_MANAGEMENT_SYSETM object sms:
  - ∵ *call by value*, `sms.add_rs(o)` attempts the following assignment (i.e., replace parameter rs by a copy of argument o):

    ```
    rs := o
    ```

  - Whether this argument passing is valid depends on o's *static type*.

Rule: In the signature of a feature m, if the type of a parameter is class C, then we may call feature m by passing objects whose *static types* are C's *descendants*.

Polymorphism: Feature Call Arguments (2)

```
test_polymorphism_feature_arguments
 local
   s1, s2, s3: STUDENT
   rs: RESIDENT_STUDENT ; nrs: NON_RESIDENT_STUDENT
   sms: STUDENT_MANAGEMENT_SYSTEM
 do
   create sms.make
   create {STUDENT} s1.make ("s1")
   create {RESIDENT_STUDENT} s2.make ("s2")
   create {NON_RESIDENT_STUDENT} s3.make ("s3")
   create {RESIDENT_STUDENT} rs.make ("rs")
   create {NON_RESIDENT_STUDENT} nrs.make ("nrs")
   sms.add_s (s1) ✓ sms.add_s (s2) ✓ sms.add_s (s3) ✓
   sms.add_s (rs) ✓ sms.add_s (nrs) ✓
   sms.add_rs (s1) × sms.add_rs (s2) × sms.add_rs (s3) ×
   sms.add_rs (rs) ✓ sms.add_rs (nrs) ×
   sms.add_nrs (s1) × sms.add_nrs (s2) × sms.add_nrs (s3) ×
   sms.add_nrs (rs) × sms.add_nrs (nrs) ✓
 end
```

Why Inheritance: A Polymorphic Collection of Students

How do you define a class `STUDENT_MANAGEMENT_SYSETM` that contains a list of *resident* and *non-resident* students?

```
class STUDENT_MANAGEMENT_SYSETM
 students: LINKED_LIST[STUDENT]
 add_student(s: STUDENT)
  do
   students.extend (s)
  end
 registerAll (c: COURSE)
  do
   across
    students as s
   loop
    s.item.register (c)
   end
  end
end
```


Polymorphism and Dynamic Binding: A Polymorphic Collection of Students

```
test_sms_polymorphism: BOOLEAN
 local
  rs: RESIDENT_STUDENT
  nrs: NON_RESIDENT_STUDENT
  c: COURSE
  sms: STUDENT_MANAGEMENT_SYSTEM
 do
  create rs.make ("Jim")
  rs.set_pr (1.5)
  create nrs.make ("Jeremy")
  nrs.set_dr (0.5)
  create sms.make
  sms.add_s (rs)
  sms.add_s (nrs)
  create c.make ("EECS3311", 500)
  sms.register_all (c)
  Result := sms.ss[1].tuition = 750 and sms.ss[2].tuition = 250
 end
```


Polymorphism: Return Values (1)

```
1  class STUDENT_MANAGEMENT_SYSTEM {
2   ss: LINKED_LIST[STUDENT]
3   add_s (s: STUDENT)
4    do
5     ss.extend (s)
6    end
7   get_student(i: INTEGER): STUDENT
8    require 1 <= i and i <= ss.count
9    do
10    Result := ss[i]
11   end
12 end
```

- **L2**: ***ST*** of each stored item (`ss[i]`) in the list: [`STUDENT`]
- **L3**: ***ST*** of input parameter `s`: [`STUDENT`]
- **L7**: ***ST*** of return value (`Result`) of `get_student`: [`STUDENT`]
- **L11**: `ss[i]`'s ***ST*** is *descendant* of `Result`' ***ST***.

  Question: What can be the ***dynamic type*** of `s` after **Line 11**?

  Answer: All descendant classes of `Student`.

Polymorphism: Return Values (2)

```
1  test_sms_polymorphism: BOOLEAN
2  local
3   rs: RESIDENT_STUDENT ; nrs: NON_RESIDENT_STUDENT
4   c: COURSE ; sms: STUDENT_MANAGEMENT_SYSTEM
5  do
6   create rs.make ("Jim") ; rs.set_pr (1.5)
7   create nrs.make ("Jeremy") ; nrs.set_dr (0.5)
8   create sms.make ; sms.add_s (rs) ; sms.add_s (nrs)
9   create c.make ("EECS3311", 500) ; sms.register_all (c)
10  Result :=
11       get_student(1).tuition = 750
12   and get_student(2).tuition = 250
13 end
```

- **L11**: `get_student(1)`'s dynamic type? [*RESIDENT_STUDENT*]
- **L11**: Version of `tuition`? [*RESIDENT_STUDENT*]
- **L12**: `get_student(2)`'s dynamic type? [*NON_RESIDENT_STUDENT*]
- **L12**: Version of `tuition`? [*NON_RESIDENT_STUDENT*]

Design Principle: Polymorphism

- When declaring an attribute `a: T`
  ⇒ Choose ***static type*** `T` which "accumulates" all features that you predict you will want to call on `a`.
  e.g., Choose `s: STUDENT` if you do not intend to be specific about which kind of student `s` might be.
  ⇒ Let ***dynamic binding*** determine at runtime which version of `tuition` will be called.
- What if after declaring `s: STUDENT` you find yourself often needing to *cast* `s` to `RESIDENT_STUDENT` in order to access `premium_rate`?

```
check attached {RESIDENT_STUDENT} s as rs then rs.set_pr(...) end
```

  ⇒ Your design decision should have been: `s:RESIDENT_STUDENT`
- Same design principle applies to:
  - Type of feature parameters: `f(a: T)`
  - Type of queries: `q(...): T`

Static Type vs. Dynamic Type: When to consider which?

- *Whether or not an OOP code compiles* depends only on the ***static types*** of relevant variables.
  ∵ Inferring the ***dynamic type*** statically is an *undecidable* problem that is inherently impossible to solve.
- *The behaviour of Java code being executed at runtime*
  e.g., which version of method is called
  e.g., if a **check attached** {...} **as** ... **then** ... **end** assertion error will occur

  depends on the ***dynamic types*** of relevant variables.
  ⇒ Best practice is to visualize how objects are created (by drawing boxes) and variables are re-assigned (by drawing arrows).

Summary: Type Checking Rules

CODE	CONDITION TO BE TYPE CORRECT
`x := y`	y's ***ST*** a **descendant** of x's ***ST***
`x.f(y)`	Feature f defined in x's ***ST*** y's ***ST*** a **descendant** of f's parameter's ***ST***
`z := x.f(y)`	Feature f defined in x's ***ST*** y's ***ST*** a **descendant** of f's parameter's ***ST*** ***ST*** of m's return value a **descendant** of z's ***ST***
check attached {C} y **then** ... **end**	C an **ancestor** or a **descendant** of y's ***ST***
check attached {C} y **as** temp **then** x := temp **end**	C an **ancestor** or a **descendant** of y's ***ST*** C a **descendant** of x's ***ST***
check attached {C} y **as** temp **then** x.f(temp) **end**	C an **ancestor** or a **descendant** of y's ***ST*** Feature f defined in x's ***ST*** C a **descendant** of f's parameter's ***ST***

Even if **check attached** {C} y **then** ... **end** compiles, a runtime assertion error occurs if C is not an **ancestor** of y's ***DT***!

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Generics

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Motivating Example: A Book of Any Objects

```
class BOOK
  names: ARRAY[STRING]
  records: ARRAY[ANY]
  -- Create an empty book
  make do ... end
  -- Add a name-record pair to the book
  add (name: STRING; record: ANY) do ... end
  -- Return the record associated with a given name
  get (name: STRING): ANY do ... end
end
```

Question: Which line has a type error?

```
1 birthday: DATE; phone_number: STRING
2 b: BOOK; is_wednesday: BOOLEAN
3 create {BOOK} b.make
4 phone_number := "416-677-1010"
5 b.add ("SuYeon", phone_number)
6 create {DATE} birthday.make(1975, 4, 10)
7 b.add ("Yuna", birthday)
8 is_wednesday := b.get("Yuna").get_day_of_week = 4
```


Motivating Example: Observations (1)

- In the BOOK class:
  - In the attribute declaration

    ```
    records: ARRAY[ANY]
    ```

    - ***ANY*** is the most general type of records.
    - Each book instance may store any object whose *static type* is a *descendant class* of ***ANY***.
  - Accordingly, from the return type of the get feature, we only know that the returned record has the static type ***ANY***, but not certain about its *dynamic type* (e.g., DATE, STRING, *etc.*).
    ∴ a record retrieved from the book, e.g., b.get("Yuna"), may only be called upon features defined in its *static type* (i.e,. ***ANY***).
- In the tester code of the BOOK class:
  - In **Line 1**, the *static types* of variables birthday (i.e., DATE) and phone_number (i.e., STRING) are *descendant classes* of ANY.
    ∴ **Line 5** and **Line 7** compile.

Motivating Example: Observations (2)

Due to *polymorphism*, in a collection, the *dynamic types* of stored objects (e.g., phone_number and birthday) need not be the same.

- Features specific to the *dynamic types* (e.g., get_day_of_week of class Date) may be new features that are not inherited from ANY.
- This is why **Line 8** would fail to compile, and may be fixed using an explicit *cast*:

  ```
  check attached {DATE} b.get("Yuna") as yuna_bday then
    is_wednesday := yuna_bday.get_day_of_week = 4
  end
  ```

- But what if the *dynamic type* of the returned object is not a DATE?

  ```
  check attached {DATE} b.get("SuYeon") as suyeon_bday then
    is_wednesday := suyeon_bday.get_day_of_week = 4
  end
  ```

  ⇒ An *assertion violation* at *runtime*!

Motivating Example: Observations (2.1)

- It seems that a combination of `attached` check (similar to an `instanceof` check in Java) and type cast can work.
- Can you see any potential problem(s)?
- **Hints:**
  - Extensibility and Maintainability
  - What happens when you have a large number of records of distinct *dynamic types* stored in the book (e.g., DATE, STRING, PERSON, ACCOUNT, ARRAY_CONTAINER, DICTIONARY, *etc.*)? [all classes are descendants of ***ANY***]

Motivating Example: Observations (2.2)

Imagine that the tester code (or an application) stores 100 different record objects into the book.

```
rec1: C1
... -- declarations of rec2 to rec99
rec100: C100
create {C1} rec1.make(...) ; b.add(..., rec1)
... -- additions of rec2 to rec99
create {C100} rec100.make(...) ; b.add(..., rec100)
```

where ***static types*** C1 to C100 are *descendant classes* of ANY.

- *Every time* you retrieve a record from the book, you need to check "exhaustively" on its *dynamic type* before calling some feature(s).

```
-- assumption: 'f1' specific to C1, 'f2' specific to C2, etc.
check attached {C1} b.get("Jim") as c1 then c1.f1 end
... -- casts for C2 to C99
check attached {C100} b.get("Jim") as c100 then c100.f100 end
```

- Writing out this list multiple times is tedious and error-prone!

Motivating Example: Observations (3)

We need a solution that:

- Eliminates runtime assertion violations due to wrong casts
- Saves us from explicit `attached` checks and type casts

As a sketch, this is how the solution looks like:

- When the user declares a BOOK object b, they must commit to the kind of record that b stores at runtime.
  e.g., b stores either DATE objects (and its *descendants*) only or String objects (and its *descendants*) only, but *not a mix*.
- When attempting to store a new record object rec into b, if rec's *static type* is not a *descendant class* of the type of book that the user previously commits to, then:
  - It is considered as a ***compilation error***
  - Rather than triggering a ***runtime assertion violation***
- When attempting to retrieve a record object from b, there is *no longer a need* to check and cast.
  ∵ *Static types* of all records in b are guaranteed to be the same.

Parameters

- In mathematics:
  - The same *function* is applied with different *argument values*.
    e.g., 2 + 3, 1 + 1, 10 + 101, *etc.*
  - We *generalize* these instance applications into a definition.
    e.g., $+ : (\mathbb{Z} \times \mathbb{Z}) \rightarrow \mathbb{Z}$ is a function that takes two integer *parameters* and returns an integer.
- In object-oriented programming:
  - We want to call a *feature*, with different *argument values*, to achieve a similar goal.
    e.g., `acc.deposit(100)`, `acc.deposit(23)`, *etc.*
  - We *generalize* these possible feature calls into a definition.
    e.g., In class ACCOUNT, a feature `deposit(amount: REAL)` takes a real-valued *parameter*.
- When you design a mathematical function or a class feature, always consider the list of *parameters*, each of which representing a set of possible *argument values*.

Generics: Design of a Generic Book

```
class BOOK[ G ]
  names: ARRAY[STRING]
  records: ARRAY[ G ]
  -- Create an empty book
  make do ... end
  /* Add a name-record pair to the book */
  add (name: STRING; record: G ) do ... end
  /* Return the record associated with a given name */
  get (name: STRING): G do ... end
end
```

Question: Which line has a type error?

```
1  birthday: DATE; phone_number: STRING
2  b: BOOK[DATE] ; is_wednesday: BOOLEAN
3  create BOOK[DATE] b.make
4  phone_number = "416-67-1010"
5  b.add ("SuYeon", phone_number)
6  create {DATE} birthday.make (1975, 4, 10)
7  b.add ("Yuna", birthday)
8  is_wednesday := b.get("Yuna").get_day_of_week == 4
```


Generics: Observations

- In class BOOK:
  - At the class level, we *parameterize the type of records* :

    ```
    class BOOK[G]
    ```

  - Every occurrence of ANY is replaced by E.
- As far as a client of BOOK is concerned, they must *instantiate* G.
  ⇒ This particular instance of book must consistently store items of that instantiating type.
- As soon as E instantiated to some known type (e.g., DATE, STRING), every occurrence of E will be replaced by that type.
- For example, in the tester code of BOOK:
  - In **Line 2**, we commit that the book b will store DATE objects only.
  - **Line 5** fails to compile. [∵ STRING not **descendant** of DATE]
  - **Line 7** still compiles. [∵ DATE is **descendant** of itself]
  - **Line 8** does *not need* any attached check and type cast, and does *not cause* any runtime assertion violation.
    ∵ All attempts to store non-DATE objects are caught at ***compile time***.

Bad Example of using Generics

Has the following client made an appropriate choice?

```
book: BOOK[ANY]
```

NO!!!!!!!!!!!!!!!!!!!!!!

- It allows **all** kinds of objects to be stored.
  ∵ All classes are descendants of ***ANY***.
- We can expect **very little** from an object retrieved from this book.
  ∵ The ***static type*** of book's items are ***ANY***, root of the class hierarchy, has the *minimum* amount of features available for use.
  ∵ Exhaustive list of casts are unavoidable.
  [***bad*** for extensibility and maintainability]

Instantiating Generic Parameters

- Say the **supplier** provides a generic DICTIONARY class:

```
class DICTIONARY[V, K] -- V type of values; K type of keys
  add_entry (v: V; k: K) do ... end
  remove_entry (k: K) do ... end
end
```

- **Clients** use DICTIONARY with different degrees of instantiations:

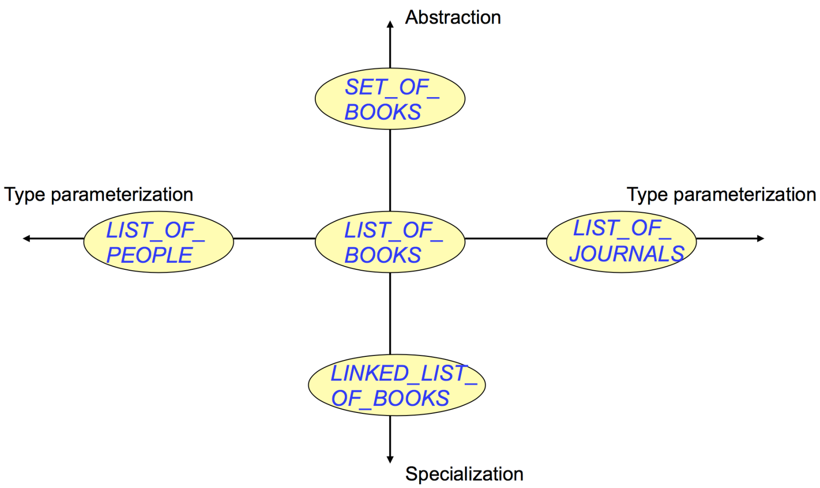
```
class DATABASE_TABLE[K, V]
  imp: DICTIONARY[V, K]
end
```

e.g., Declaring `DATABSE_TABLE[INTEGER, STRING]` instantiates `DICTIONARY[STRING, INTEGER]`.

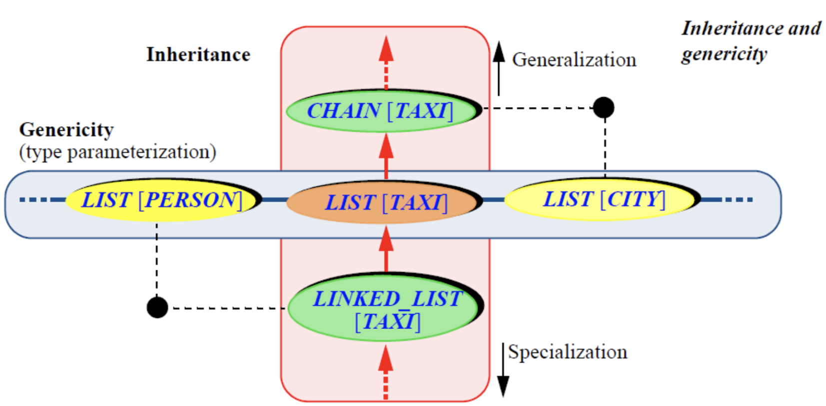
```
class STUDENT_BOOK[V]
  imp: DICTIONARY[V, STRING]
end
```

e.g., Declaring `STUDENT_BOOK[ARRAY[COURSE]]` instantiates `DICTIONARY[ARRAY[COURSE], STRING]`.

Generics vs. Inheritance (1)



Generics vs. Inheritance (2)



Beyond this lecture . . .

- Study the “Generic Parameters and the Iterator Pattern” Tutorial Videos.

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Abstractions via Mathematical Models

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Motivating Problem: Complete Contracts

- Recall what we learned in the *Complete Contracts* lecture:
  - In *post-condition*, for *each attribute*, specify the relationship between its ***pre-state*** value and its ***post-state*** value.
  - Use the **old** keyword to refer to ***post-state*** values of expressions.
  - For a ***composite***-structured attribute (e.g., arrays, linked-lists, hash-tables, *etc.*), we should specify that after the update:
    1. The intended change is present; **and**
    2. *The rest of the structure is unchanged* .
- Let's now revisit this technique by specifying a *LIFO stack*.

Motivating Problem: LIFO Stack (1)

- Let's consider three different implementation strategies:

Stack Feature	Array	Linked List	
	Strategy 1	Strategy 2	Strategy 3
count	imp.count		
top	imp[imp.count]	imp.first	imp.last
push(g)	imp.force(g, imp.count + 1)	imp.put_front(g)	imp.extend(g)
pop	imp.list.remove_tail (1)	list.start list.remove	imp.finish imp.remove

- Given that all strategies are meant for implementing the ***same ADT***, will they have *identical* contracts?

Motivating Problem: LIFO Stack (2.1)

```
class LIFO_STACK[G] create make
feature {NONE} -- Strategy 1: array
  imp: ARRAY[G]
feature -- Initialization
  make do create imp.make_empty ensure imp.count = 0 end
feature -- Commands
  push(g: G)
    do imp.force(g, imp.count + 1)
    ensure
      changed: imp[count] ~ g
      unchanged: across 1 |..| count - 1 as i all
                  imp[i.item] ~ (old imp.deep_twin)[i.item] end
    end
  pop
    do imp.remove_tail(1)
    ensure
      changed: count = old count - 1
      unchanged: across 1 |..| count as i all
                  imp[i.item] ~ (old imp.deep_twin)[i.item] end
    end
```

Motivating Problem: LIFO Stack (2.2)

```
class LIFO_STACK[G] create make
feature {NONE} -- Strategy 2: linked-list first item as top
 imp: LINKED_LIST[G]
feature -- Initialization
 make do create imp.make ensure imp.count = 0 end
feature -- Commands
 push(g: G)
   do imp.put_front(g)
   ensure
     changed: imp.first ~ g
     unchanged: across 2 |..| count as i all
                imp[i.item] ~ (old imp.deep_twin)[i.item - 1] end
   end
 pop
   do imp.start ; imp.remove
   ensure
     changed: count = old count - 1
     unchanged: across 1 |..| count as i all
                imp[i.item] ~ (old imp.deep_twin)[i.item + 1] end
   end
```


Motivating Problem: LIFO Stack (2.3)

```
class LIFO_STACK[G] create make
feature {NONE} -- Strategy 3: linked-list last item as top
 imp: LINKED_LIST[G]
feature -- Initialization
 make do create imp.make ensure imp.count = 0 end
feature -- Commands
 push(g: G)
   do imp.extend(g)
   ensure
     changed: imp.last ~ g
     unchanged: across 1 |..| count - 1 as i all
                imp[i.item] ~ (old imp.deep_twin)[i.item] end
   end
 pop
   do imp.finish ; imp.remove
   ensure
     changed: count = old count - 1
     unchanged: across 1 |..| count as i all
                imp[i.item] ~ (old imp.deep_twin)[i.item] end
   end
```


Motivating Problem: LIFO Stack (3)

- *Postconditions* of all 3 versions of stack are *complete*.
  i.e., Not only the new item is ***pushed/popped***, but also the remaining part of the stack is ***unchanged***.
- But they violate the principle of *information hiding*:
  Changing the ***secret***, internal workings of data structures should not affect any existing clients.
- How so?
  The private attribute `imp` is referenced in the *postconditions*, exposing the implementation strategy not relevant to clients:
  - Top of stack may be `imp[count]`, `imp.first`, or `imp.last`.
  - Remaining part of stack may be `across 1 |..| count - 1` or `across 2 |..| count`.

  ⇒ *Changing the implementation strategy* from one to another will also *change the contracts for **all** features*.

  ⇒ This also violates the *Single Choice Principle*.

Math Models: Command vs Query

- Use MATHMODELS library to create math objects (SET, REL, SEQ).
- State-changing ***commands***: Implement an *Abstraction Function*

```
class LIFO_STACK[G -> attached ANY] create make
feature {NONE} -- Implementation
 imp: LINKED_LIST[G]
feature -- Abstraction function of the stack ADT
 model: SEQ[G]
   do create Result.make_empty
      across imp as cursor loop Result.append(cursor.item) end
   end
```

- Side-effect-free ***queries***: Write Complete Contracts

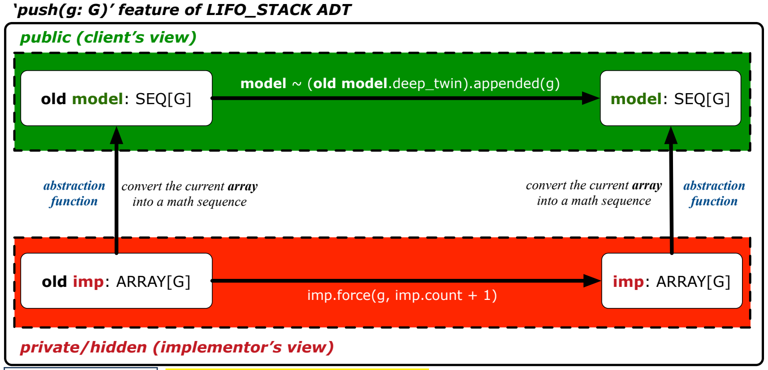
```
class LIFO_STACK[G -> attached ANY] create make
feature -- Abstraction function of the stack ADT
 model: SEQ[G]
feature -- Commands
 push (g: G)
  ensure model ~ (old model.deep_twin).appended(g) end
```

Implementing an Abstraction Function (1)

```
class LIFO_STACK[G -> attached ANY] create make
feature {NONE} -- Implementation Strategy 1
  imp: ARRAY[G]
feature -- Abstraction function of the stack ADT
  model: SEQ[G]
    do create Result.make_from_array (imp)
    ensure
      counts: imp.count = Result.count
      contents: across 1 |..| Result.count as i all
                  Result[i.item] ~ imp[i.item]
    end
feature -- Commands
  make do create imp.make_empty ensure model.count = 0 end
  push (g: G) do imp.force(g, imp.count + 1)
    ensure pushed: model ~ (old model.deep_twin).appended(g) end
  pop do imp.remove_tail(1)
    ensure popped: model ~ (old model.deep_twin).front end
end
```


Abstracting ADTs as Math Models (1)

'push(g: G)' feature of LIFO_STACK ADT



- **Strategy 1** *Abstraction function*: Convert the *implementation array* to its corresponding *model sequence*.
- *Contract* for the `put(g: G)` feature remains the ***same***:

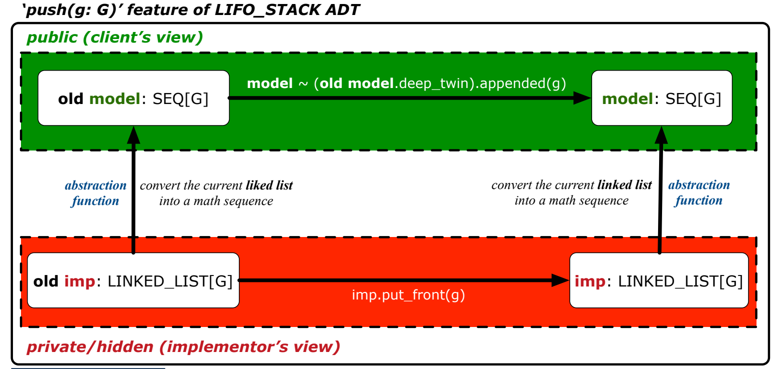
```
model ~ (old model.deep_twin).appended(g)
```


Implementing an Abstraction Function (2)

```
class LIFO_STACK[G -> attached ANY] create make
feature {NONE} -- Implementation Strategy 2 (first as top)
  imp: LINKED_LIST[G]
feature -- Abstraction function of the stack ADT
  model: SEQ[G]
    do create Result.make_empty
      across imp as cursor loop Result.prepend(cursor.item) end
    ensure
      counts: imp.count = Result.count
      contents: across 1 |..| Result.count as i all
                  Result[i.item] ~ imp[count - i.item + 1]
    end
feature -- Commands
  make do create imp.make ensure model.count = 0 end
  push (g: G) do imp.put_front(g)
    ensure pushed: model ~ (old model.deep_twin).appended(g) end
  pop do imp.start ; imp.remove
    ensure popped: model ~ (old model.deep_twin).front end
end
```


Abstracting ADTs as Math Models (2)

'push(g: G)' feature of LIFO_STACK ADT



- **Strategy 2** *Abstraction function*: Convert the *implementation list* (first item is top) to its corresponding *model sequence*.
- *Contract* for the `put(g: G)` feature remains the ***same***:

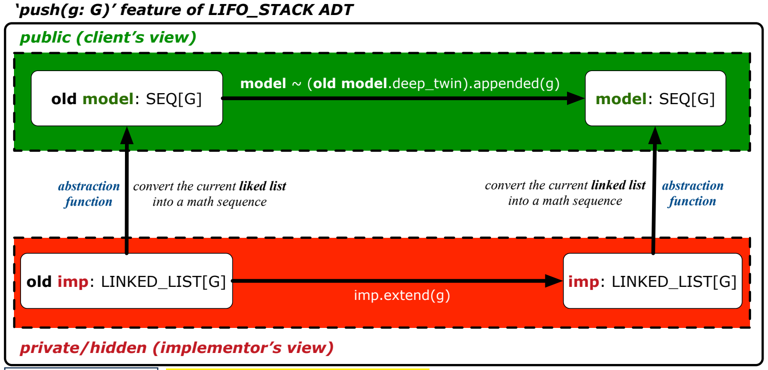
```
model ~ (old model.deep_twin).appended(g)
```

Implementing an Abstraction Function (3)

```
class LIFO_STACK[G -> attached ANY] create make
feature {NONE} -- Implementation Strategy 3 (last as top)
  imp: LINKED_LIST[G]
feature -- Abstraction function of the stack ADT
  model: SEQ[G]
    do create Result.make_empty
       across imp as cursor loop Result.append(cursor.item) end
    ensure
      counts: imp.count = Result.count
      contents: across 1 |..| Result.count as i all
                  Result[i.item] ~ imp[i.item]
    end
feature -- Commands
  make do create imp.make ensure model.count = 0 end
  push (g: G) do imp.extend(g)
    ensure pushed: model ~ (old model.deep_twin).appended(g) end
  pop do imp.finish ; imp.remove
    ensure popped: model ~ (old model.deep_twin).front end
end
```


Abstracting ADTs as Math Models (3)

'push(g: G)' feature of LIFO_STACK ADT



- **Strategy 3** *Abstraction function*: Convert the *implementation list* (last item is top) to its corresponding *model sequence*.
- *Contract* for the `put(g: G)` feature remains the ***same***:

```
model ~ (old model.deep_twin).appended(g)
```


Solution: Abstracting ADTs as Math Models

- Writing contracts in terms of *implementation attributes* (arrays, LL's, hash tables, *etc.*) violates *information hiding* principle.
- Instead:
  - For each ADT, create an *abstraction* via a ***mathematical model***.
    e.g., Abstract a `LIFO_STACK` as a mathematical sequence.
  - For each ADT, define an *abstraction function* (i.e., a query) whose return type is a kind of ***mathematical model***.
    e.g., Convert *implementation array* to *mathematical sequence*
  - Write contracts in terms of the ***abstract math model***.
    e.g., When pushing an item *g* onto the stack, specify it as appending *g* into its model sequence.
  - Upon *changing the implementation*:
    - **No** change on **what** the abstraction is, hence *no change on contracts*.
    - **Only** change **how** the abstraction is constructed, hence *changes on the body of the abstraction function*.
      e.g., Convert *implementation linked-list* to *mathematical sequence*
      ⇒ The *Single Choice Principle* is obeyed.

Math Review: Set Definitions and Membership

- A *set* is a collection of objects.
  - Objects in a set are called its *elements* or *members*.
  - *Order* in which elements are arranged does not matter.
  - An element can appear *at most once* in the set.
- We may define a set using:
  - *Set Enumeration*: Explicitly list all members in a set.
    e.g., $\{1, 3, 5, 7, 9\}$
  - *Set Comprehension*: Implicitly specify the condition that all members satisfy.
    e.g., $\{x \mid 1 \leq x \leq 10 \wedge x \texttt{ is an odd number}\}$
- An empty set (denoted as $\{\}$ or $\varnothing$) has no members.
- We may check if an element is a *member* of a set:
  e.g., $5 \in \{1, 3, 5, 7, 9\}$ [*true*]
  e.g., $4 \notin \{x \mid x \leq 1 \leq 10, x \texttt{ is an odd number}\}$ [*true*]
- The number of elements in a set is called its *cardinality*.
  e.g., $|\varnothing| = 0$, $|\{x \mid x \leq 1 \leq 10, x \texttt{ is an odd number}\}| = 5$

Math Review: Set Relations

Given two sets S_1 and S_2:

- S_1 is a *subset* of S_2 if every member of S_1 is a member of S_2.

$$S_1 \subseteq S_2 \iff (\forall x \bullet x \in S_1 \Rightarrow x \in S_2)$$

- S_1 and S_2 are *equal* iff they are the subset of each other.

$$S_1 = S_2 \iff S_1 \subseteq S_2 \land S_2 \subseteq S_1$$

- S_1 is a *proper subset* of S_2 if it is a strictly smaller subset.

$$S_1 \subset S_2 \iff S_1 \subseteq S_2 \land |S1| < |S2|$$

Math Review: Set Operations

Given two sets S_1 and S_2:

- *Union* of S_1 and S_2 is a set whose members are in either.

$$S_1 \cup S_2 = \{x \mid x \in S_1 \lor x \in S_2\}$$

- *Intersection* of S_1 and S_2 is a set whose members are in both.

$$S_1 \cap S_2 = \{x \mid x \in S_1 \land x \in S_2\}$$

- *Difference* of S_1 and S_2 is a set whose members are in S_1 but not S_2.

$$S_1 \setminus S_2 = \{x \mid x \in S_1 \land x \notin S_2\}$$

Math Review: Power Sets

The *power set* of a set S is a *set* of all S' *subsets*.

$$\mathbb{P}(S) = \{s \mid s \subseteq S\}$$

The power set contains subsets of *cardinalities* 0, 1, 2, ..., $|S|$.
e.g., $\mathbb{P}(\{1,2,3\})$ is a set of sets, where each member set s has cardinality 0, 1, 2, or 3:

$$\left\{\begin{array}{l} \varnothing, \\ \{1\},\ \{2\},\ \{3\}, \\ \{1,2\},\ \{2,3\},\ \{3,1\}, \\ \{1,2,3\} \end{array}\right\}$$

Math Review: Set of Tuples

Given n sets S_1, S_2, ..., S_n, a *cross product* of theses sets is a set of n-tuples.
Each *n-tuple* $(e_1, e_2, \dots, e_n)$ contains n elements, each of which a member of the corresponding set.

$$S_1 \times S_2 \times \cdots \times S_n = \{(e_1, e_2, \dots, e_n) \mid e_i \in S_i \land 1 \le i \le n\}$$

e.g., $\{a,b\} \times \{2,4\} \times \{\$,\&\}$ is a set of triples:

$$\begin{array}{rl} & \{a,b\} \times \{2,4\} \times \{\$,\&\} \\ = & \{\ (e_1, e_2, e_3) \mid e_1 \in \{a,b\} \land e_2 \in \{2,4\} \land e_3 \in \{\$,\&\}\ \} \\ = & \{(a,2,\$),(a,2,\&),(a,4,\$),(a,4,\&), \\ & (b,2,\$),(b,2,\&),(b,4,\$),(b,4,\&)\} \end{array}$$

Math Models: Relations (1)

- A *relation* is a collection of mappings, each being an *ordered pair* that maps a member of set S to a member of set T.
  e.g., Say $S = \{1, 2, 3\}$ and $T = \{a, b\}$
  - $\varnothing$ is an empty relation.
  - $S \times T$ is a relation (say r_1) that maps from each member of S to each member in T: $\{(1, a), (1, b), (2, a), (2, b), (3, a), (3, b)\}$
  - $\{(x, y) : S \times T \mid x \neq 1\}$ is a relation (say r_2) that maps only some members in S to every member in T: $\{(2, a), (2, b), (3, a), (3, b)\}$.
- Given a relation r:
  - *Domain* of r is the set of S members that r maps from.
    $$\mathrm{dom}(r) = \{s : S \mid (\exists t \bullet (s, t) \in r)\}$$
    e.g., $\mathrm{dom}(r_1) = \{1, 2, 3\}$, $\mathrm{dom}(r_2) = \{2, 3\}$
  - *Range* of r is the set of T members that r maps to.
    $$\mathrm{ran}(r) = \{t : T \mid (\exists s \bullet (s, t) \in r)\}$$
    e.g., $\mathrm{ran}(r_1) = \{a, b\} = \mathrm{ran}(r_2)$

Math Models: Relations (2)

- We use the power set operator to express the set of *all possible relations* on S and T:
  $$\mathbb{P}(S \times T)$$
- To declare a relation variable r, we use the colon (`:`) symbol to mean *set membership*:
  $$r : \mathbb{P}(S \times T)$$
- Or alternatively, we write:
  $$r : S \leftrightarrow T$$
  where the set $S \leftrightarrow T$ is synonymous to the set $\mathbb{P}(S \times T)$

Math Models: Relations (3.1)

Say $r = \{(a, 1), (b, 2), (c, 3), (a, 4), (b, 5), (c, 6), (d, 1), (e, 2), (f, 3)\}$

- r.***domain***: set of first-elements from r
  - r.**domain** = $\{ d \mid (d, r) \in r \}$
  - e.g., r.**domain** = $\{a, b, c, d, e, f\}$
- r.***range***: set of second-elements from r
  - r.**range** = $\{ r \mid (d, r) \in r \}$
  - e.g., r.**range** = $\{1, 2, 3, 4, 5, 6\}$
- r.***inverse***: a relation like r except elements are in reverse order
  - r.**inverse** = $\{ (r, d) \mid (d, r) \in r \}$
  - e.g., r.**inverse** = $\{(1, a), (2, b), (3, c), (4, a), (5, b), (6, c), (1, d), (2, e), (3, f)\}$

Math Models: Relations (3.2)

Say $r = \{(a, 1), (b, 2), (c, 3), (a, 4), (b, 5), (c, 6), (d, 1), (e, 2), (f, 3)\}$

- r.***domain_restricted***(ds): sub-relation of r with domain ds.
  - r.**domain_restricted**(ds) = $\{ (d, r) \mid (d, r) \in r \wedge d \in ds \}$
  - e.g., r.**domain_restricted**({a, b}) = $\{(\mathbf{a}, 1), (\mathbf{b}, 2), (\mathbf{a}, 4), (\mathbf{b}, 5)\}$
- r.***domain_subtracted***(ds): sub-relation of r with domain not ds.
  - r.**domain_subtracted**(ds) = $\{ (d, r) \mid (d, r) \in r \wedge d \notin ds \}$
  - e.g., r.**domain_subtracted**({a, b}) = $\{(\mathbf{c}, 6), (\mathbf{d}, 1), (\mathbf{e}, 2), (\mathbf{f}, 3)\}$
- r.***range_restricted***(rs): sub-relation of r with range rs.
  - r.**range_restricted**(rs) = $\{ (d, r) \mid (d, r) \in r \wedge r \in rs \}$
  - e.g., r.**range_restricted**({1, 2}) = $\{(a, \mathbf{1}), (b, \mathbf{2}), (d, \mathbf{1}), (e, \mathbf{2})\}$
- r.***range_subtracted***(ds): sub-relation of r with range not ds.
  - r.**range_subtracted**(rs) = $\{ (d, r) \mid (d, r) \in r \wedge r \notin rs \}$
  - e.g., r.**range_subtracted**({1, 2}) = $\{(c, \mathbf{3}), (a, \mathbf{4}), (b, \mathbf{5}), (c, \mathbf{6})\}$

Math Models: Relations (3.3)

Say $r = \{(a,1),(b,2),(c,3),(a,4),(b,5),(c,6),(d,1),(e,2),(f,3)\}$

- r.***overridden***(t): a relation which agrees on r outside domain of t.*domain*, and agrees on t within domain of t.*domain*
  - r.**overridden**(t) = $t \cup r$.**domain_subtracted**(t.**domain**)
  -

$$
\begin{aligned}
& r.\textbf{overridden}(\underbrace{\{(a,3),(c,4)\}}_{t}) \\
= \; & \underbrace{\{(a,3),(c,4)\}}_{t} \cup \underbrace{\{(b,2),(b,5),(d,1),(e,2),(f,3)\}}_{r.\textbf{domain\_subtracted}(\underbrace{t.\textbf{domain}}_{\{a,c\}})} \\
= \; & \{(a,3),(c,4),(b,2),(b,5),(d,1),(e,2),(f,3)\}
\end{aligned}
$$

Math Review: Functions (1)

A *function* f on sets S and T is a *specialized form* of relation: it is forbidden for a member of S to map to more than one members of T.

$$\forall s : S; t_1 : T; t_2 : T \bullet (s, t_1) \in f \land (s, t_2) \in f \Rightarrow t_1 = t_2$$

e.g., Say $S = \{1,2,3\}$ and $T = \{a,b\}$, which of the following relations are also functions?

- $S \times T$ [No]
- $(S \times T) - \{(x,y) \mid (x,y) \in S \times T \land x = 1\}$ [No]
- $\{(1,a),(2,b),(3,a)\}$ [Yes]
- $\{(1,a),(2,b)\}$ [Yes]

Math Review: Functions (2)

- We use *set comprehension* to express the set of all possible functions on S and T as those relations that satisfy the *functional property*:

$$\{r : S \leftrightarrow T \mid (\forall s : S; t_1 : T; t_2 : T \bullet (s,t_1) \in r \land (s,t_2) \in r \Rightarrow t_1 = t_2)\}$$

- This set (of possible functions) is a subset of the set (of possible relations): $\mathbb{P}(S \times T)$ and $S \leftrightarrow T$.
- We abbreviate this set of possible functions as $S \rightarrow T$ and use it to declare a function variable f:

$$f : S \rightarrow T$$

Math Review: Functions (3.1)

Given a function $f : S \rightarrow T$:

- f is *injective* (or an injection) if f does not map a member of S to more than one members of T.

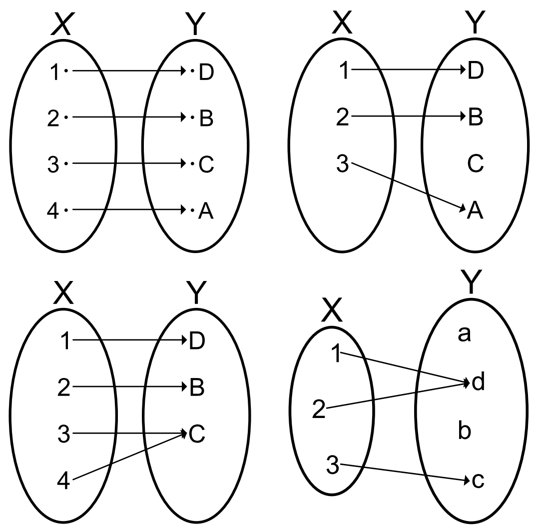
$$f \texttt{ is injective} \iff (\forall s_1 : S; s_2 : S; t : T \bullet (s_1, t) \in r \land (s_2, t) \in r \Rightarrow s_1 = s_2)$$

  e.g., Considering an array as a function from integers to objects, being injective means that the array does not contain any duplicates.
- f is *surjective* (or a surjection) if f maps to all members of T.

$$f \texttt{ is surjective} \iff \mathrm{ran}(f) = T$$

- f is *bijective* (or a bijection) if f is both injective and surjective.

Math Review: Functions (3.2)



Math Models: Command-Query Separation

Command	*Query*
`domain_restrict`	`domain_restricted`
`domain_restrict_by`	`domain_restricted_by`
`domain_subtract`	`domain_subtracted`
`domain_subtract_by`	`domain_subtracted_by`
`range_restrict`	`range_restricted`
`range_restrict_by`	`range_restricted_by`
`range_subtract`	`range_subtracted`
`range_subtract_by`	`range_subtracted_by`
`override`	`overridden`
`override_by`	`overridden_by`

Say $r = \{(a,1),(b,2),(c,3),(a,4),(b,5),(c,6),(d,1),(e,2),(f,3)\}$

- ***Commands*** modify the context relation objects.
  `r.domain_restrict({a})` changes r to $\{(a,1),(a,4)\}$
- ***Queries*** return new relations without modifying context objects.
  `r.domain_restricted({a})` returns $\{(a,1),(a,4)\}$ with r untouched

Math Models: Example Test

```
test_rel: BOOLEAN
  local
    r, t: REL[STRING, INTEGER]
    ds: SET[STRING]
  do
    create r.make_from_tuple_array (
      <<["a", 1], ["b", 2], ["c", 3],
        ["a", 4], ["b", 5], ["c", 6],
        ["d", 1], ["e", 2], ["f", 3]>>)
    create ds.make_from_array (<<"a">>)
    -- r is not changed by the query 'domain_subtracted'
    t := r.domain_subtracted (ds)
    Result :=
      t /~ r and not t.domain.has ("a") and r.domain.has ("a")
    check Result end
    -- r is changed by the command 'domain_subtract'
    r.domain_subtract (ds)
    Result :=
      t ~ r and not t.domain.has ("a") and not r.domain.has ("a")
  end
```

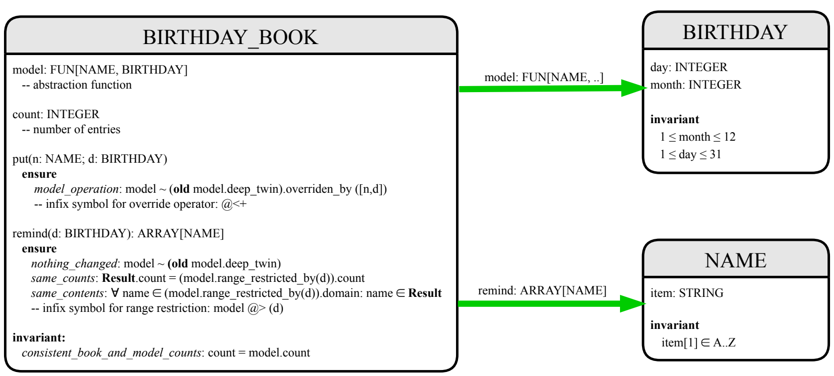

Case Study: A Birthday Book

- A birthday book stores a collection of entries, where each entry is a pair of a person's name and their birthday.
- No two entries stored in the book are allowed to have the same name.
- Each birthday is characterized by a month and a day.
- A birthday book is first created to contain an empty collection of entires.
- Given a birthday book, we may:
  - Inquire about the number of entries currently stored in the book
  - Add a new entry by supplying its name and the associated birthday
  - Remove the entry associated with a particular person
  - Find the birthday of a particular person
  - Get a reminder list of names of people who share a given birthday

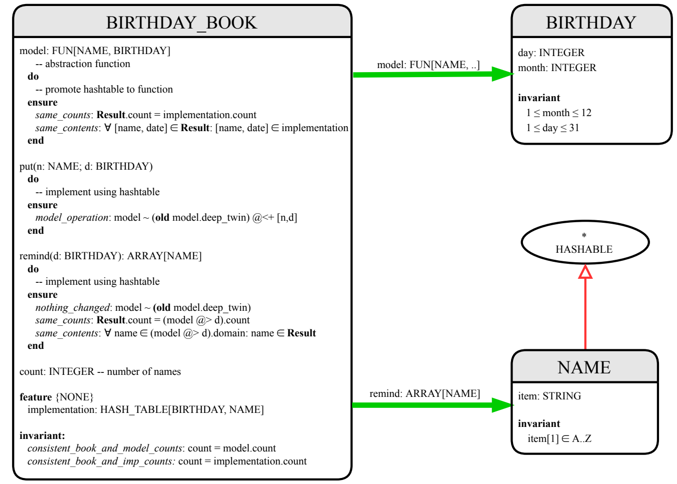
Birthday Book: Decisions

- ***Design*** Decision
  - Classes
  - Client Supplier vs. Inheritance
  - Mathematical Model? [e.g., REL or FUN]
  - Contracts
- ***Implementation*** Decision
  - Two linear structures (e.g., arrays, lists) [$O(n)$]
  - A balanced search tree (e.g., AVL tree) [$O(log \cdot n)$]
  - A hash table [$O(1)$]
- Implement an *abstract function* that maps implementation to the math model.

Birthday Book: Design



Birthday Book: Implementation



Beyond this lecture . . .

- Familiarize yourself with the features of classes SEQ, REL, FUN, and SET for the lab test.
- Play with the source code of the Birthday Book example: https://github.com/yuselg/eiffel/tree/master/snippets/birthday-book.
- **Exercise**:
  - Consider an alternative implementation using two linear structures (e.g., here in Java).
  - Create another LINEAR_BIRTHDAY_BOOK class and modify the implementation of abstraction function accordingly. Do all contracts still pass?

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The Composite Design Pattern

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

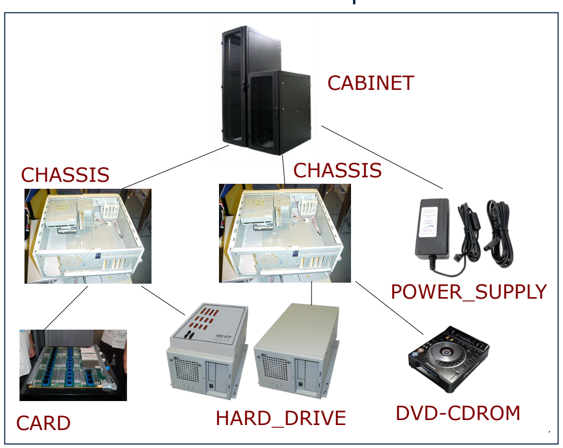
Motivating Problem (1)

- Many manufactured systems, such as computer systems or stereo systems, are composed of ***individual components*** and ***sub-systems*** that contain components.

  e.g., A computer system is composed of:
  - Individual pieces of equipment (*hard drives*, *cd-rom drives*)
    Each equipment has *properties* : e.g., power consumption and cost.
  - Composites such as *cabinets*, *busses*, and *chassis*
    Each *cabinet* contains various types of *chassis*, each of which in turn containing components (*hard-drive*, *power-supply*) and *busses* that contain *cards*.
- Design a system that will allow us to easily *build* systems and *calculate* their total cost and power consumption.

Motivating Problem (2)

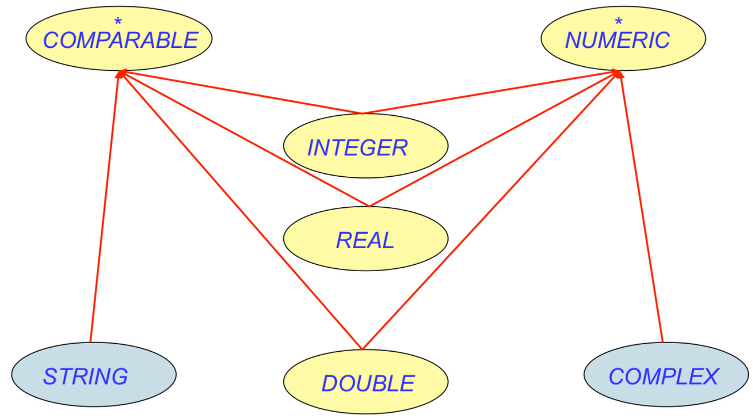
Design for *tree structures* with whole-part *hierarchies*.



Challenge : There are ***base*** and ***recursive*** modelling artifacts.

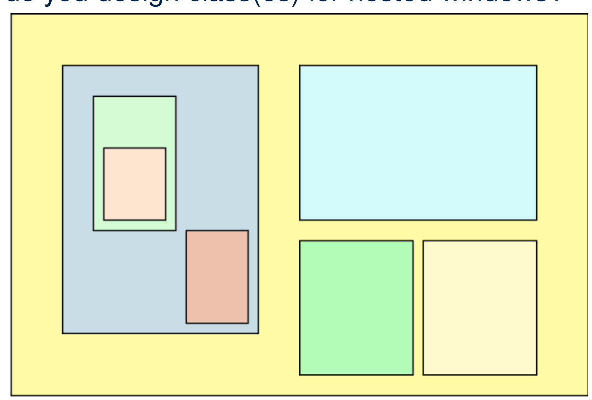
Multiple Inheritance: Combining Abstractions (1)

A class may have two more parent classes.



MI: Combining Abstractions (2.1)

Q: How do you design class(es) for nested windows?



Hints: height, width, xpos, ypos, change width, change height, move, parent window, descendant windows, add child window

MI: Combining Abstractions (2)

A: Separating *Graphical* features and *Hierarchical* features

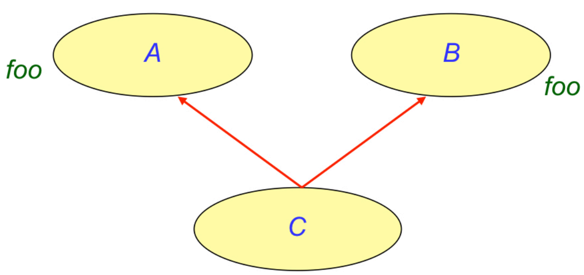
```
class RECTANGLE
  feature -- Queries
    width, height: REAL
    xpos, ypos: REAL
  feature -- Commands
    make (w, h: REAL)
    change_width
    change_height
    move
end
```

```
class TREE[G]
  feature -- Queries
    parent: TREE[G]
    descendants: LIST[TREE[G]]
  feature -- Commands
    add_child (c: TREE[G])
end
```

```
class WINDOW
  inherit
    RECTANGLE
    TREE[WINDOW]
feature
  add (w: WINDOW)
end
```

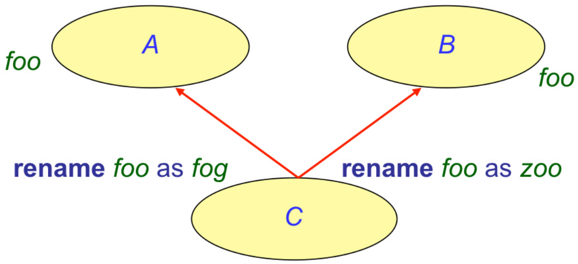
```
test_window: BOOLEAN
  local w1, w2, w3, w4: WINDOW
  do
    create w1.make(8, 6) ; create w2.make(4, 3)
    create w3.make(1, 1) ; create w4.make(1, 1)
    w2.add(w4) ; w1.add(w2) ; w1.add(w3)
    Result := w1.descendants.count = 2
  end
```


MI: Name Clashes



In class `C`, feature `foo` inherited from ancestor class `A` clashes with feature `foo` inherited from ancestor class `B`.

MI: Resolving Name Clashes



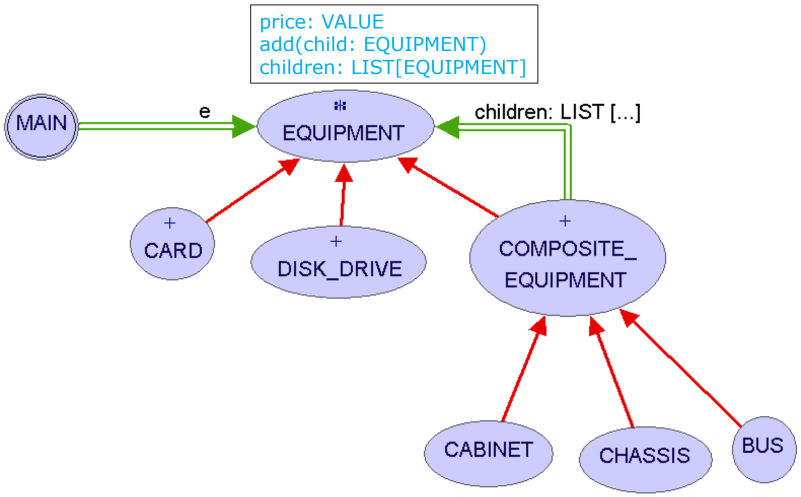

```
class C
  inherit
    A rename foo as fog end
    B rename foo as zoo end
  ...
```

	o.foo	o.fog	o.zoo
o: A	✓	×	×
o: B	✓	×	×
o: C	×	✓	✓

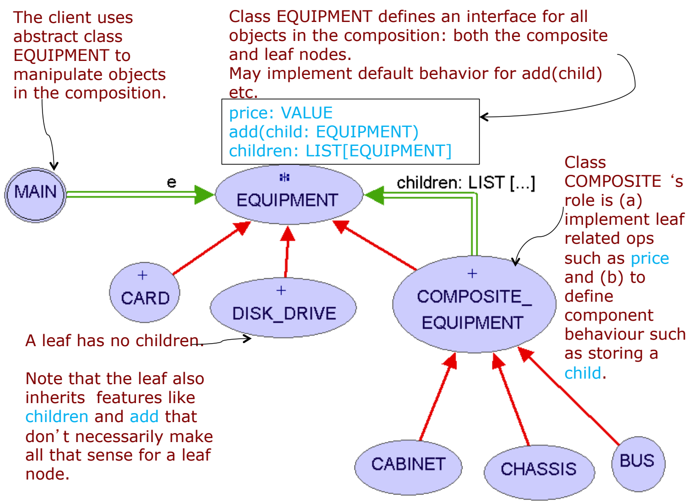
Solution: The Composite Pattern

- **Design**: Categorize into *base* artifacts or *recursive* artifacts.
- **Programming**:
  Build a *tree structure* representing the whole-part *hierarchy*.
- **Runtime**:
  Allow clients to treat *base* objects (leafs) and *recursive* compositions (nodes) *uniformly*.
  ⇒ *Polymorphism*: *leafs* and *nodes* are "substitutable".
  ⇒ *Dynamic Binding*: Different versions of the same operation is applied on *individual objects* and *composites*.
  e.g., Given `e: EQUIPMENT`:
  - `e.price` may return the unit price of a ***DISK_DRIVE***.
  - `e.price` may sum prices of a ***CHASIS***' containing equipments.

Composite Architecture: Design (1.1)



Composite Architecture: Design (1.2)



Composite Architecture: Design (1.3)

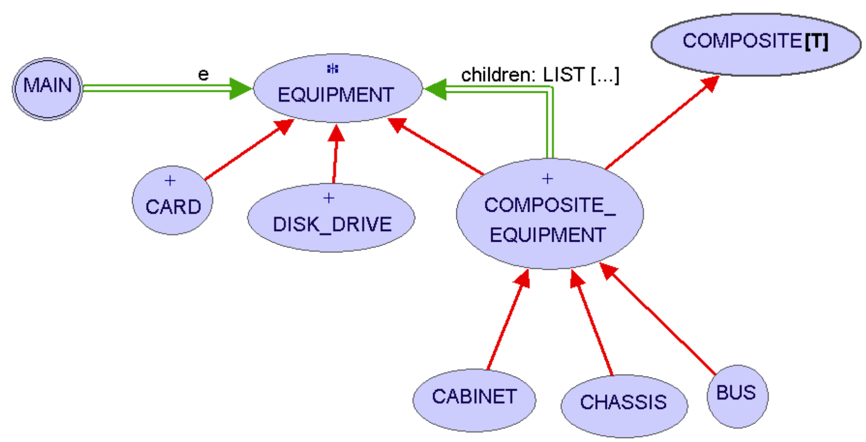
Q: Any flaw of this first design?

A: Two "composite" features defined at the `EQUIPMENT` level:

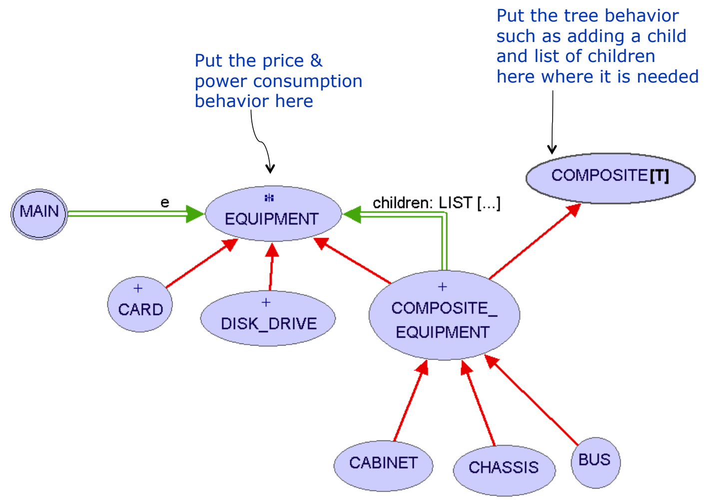
- `children: LIST[EQUIPMENT]`
- `add(child: EQUIPMENT)`

⇒ Inherited to all *base* equipments (e.g., `HARD_DRIVE`) that do not apply to such features.

Composite Architecture: Design (2.1)



Composite Architecture: Design (2.2)



Implementing the Composite Pattern (1)

```
deferred class
  EQUIPMENT
feature
  name: STRING
  price: REAL -- uniform access principle
end
```

```
class
  CARD
inherit
  EQUIPMENT
feature
  make (n: STRING; p: REAL)
    do
      name := n
      price := p -- price is an attribute
    end
end
```


Implementing the Composite Pattern (2.1)

```
deferred class
  COMPOSITE[T]
feature
  children: LINKED_LIST[T]

  add (c: T)
    do
      children.extend (c) -- Polymorphism
    end
end
```

Exercise: Make the `COMPOSITE` class *iterable*.

Implementing the Composite Pattern (2.2)

```
class
  COMPOSITE_EQUIPMENT
inherit
  EQUIPMENT
  COMPOSITE [EQUIPMENT]
create
  make
feature
  make (n: STRING)
    do name := n ; create children.make end
  price : REAL -- price is a query
      -- Sum the net prices of all sub-equipments
    do
      across
        children as cursor
      loop
        Result := Result + cursor.item.price -- dynamic binding
      end
    end
end
```

Testing the Composite Pattern

```
test_composite_equipment: BOOLEAN
 local
  card, drive: EQUIPMENT
  cabinet: CABINET -- holds a CHASSIS
  chassis: CHASSIS -- contains a BUS and a DISK_DRIVE
  bus: BUS -- holds a CARD
 do
  create {CARD} card.make("16Mbs Token Ring", 200)
  create {DISK_DRIVE} drive.make("500 GB harddrive", 500)
  create bus.make("MCA Bus")
  create chassis.make("PC Chassis")
  create cabinet.make("PC Cabinet")

  bus.add(card)
  chassis.add(bus)
  chassis.add(drive)
  cabinet.add(chassis)
  Result := cabinet.price = 700
 end
```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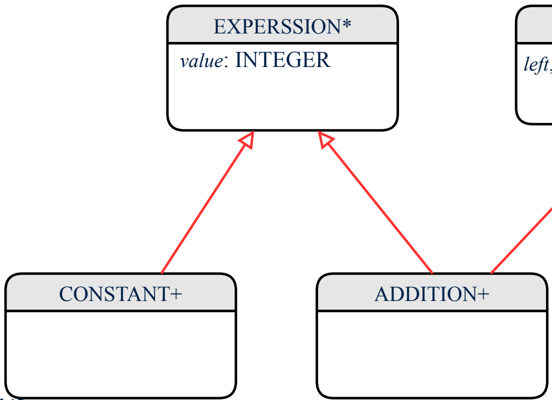
The Visitor Design Pattern

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

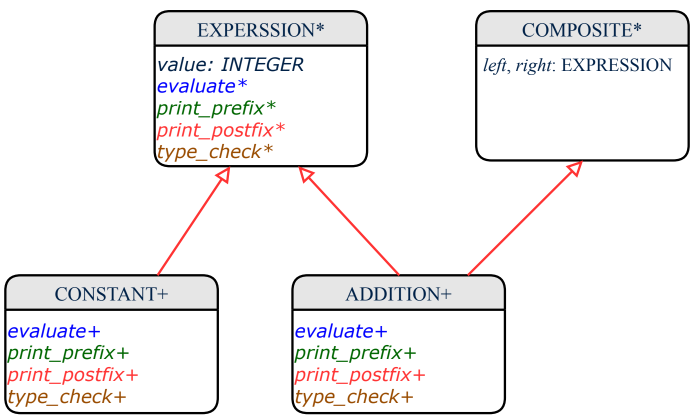
Motivating Problem (1)

Based on the *composite pattern* you learned, design classes to model *structures* of arithmetic expressions (e.g., `341`, `2`, `341 + 2`).



Motivating Problem (2)

Extend the *composite pattern* to support *operations* such as `evaluate`, pretty printing (`print_prefix`, `print_postfix`), and `type_check`.



Problems of Extended Composite Pattern

- Distributing the various **unrelated** ***operations*** across nodes of the ***abstract syntax tree*** violates the *single-choice principle* :

  To add/delete/modify an operation
  ⇒ Change of all descendants of `EXPRESSION`
- Each node class lacks in *cohesion* :

  A *class* is supposed to group *relevant* concepts in a *single* place.
  ⇒ Confusing to mix codes for evaluation, pretty printing, and type checking.
  ⇒ We want to avoid “polluting” the classes with these various unrelated operations.

Open/Closed Principle

Software entities (classes, features, etc.) should be ***open*** for *extension* , but ***closed*** for *modification* .

⇒ When *extending* the behaviour of a system, we:

- May add/modify the ***open*** (unstable) part of system.
- May not add/modify the ***closed*** (stable) part of system.

e.g., In designing the application of an expression language:

- **Alternative 1**:
  Syntactic constructs of the language may be ***closed***, whereas operations on the language may be ***open***.
- **Alternative 2**:
  Syntactic constructs of the language may be ***open***, whereas operations on the language may be ***closed***.

Visitor Pattern

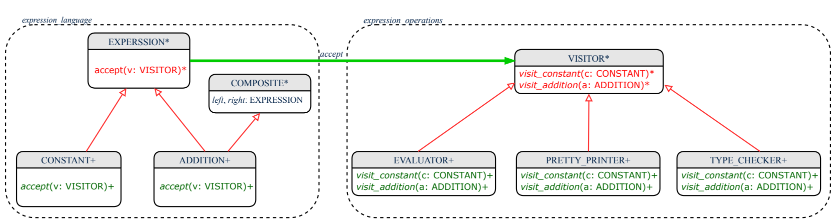
- *Separation of concerns* :
  - Set of language constructs
  - Set of operations

  ⇒ Classes from these two sets are *decoupled* and organized into two separate clusters.
- *Open-Closed Principle (OCP)* :
  - ***Closed***, staple part of system: set of language constructs
  - ***Open***, unstable part of system: set of operations

  ⇒ *OCP* helps us determine if Visitor Pattern is *applicable* .

  ⇒ If it was decided that language constructs are ***open*** and operations are ***closed***, then do **not** use Visitor Pattern.

Visitor Pattern: Architecture



Visitor Pattern Implementation: Structures

Cluster ***expression_language***

- Declare *deferred* feature `accept(v: VISITOR)` in `EXPRSSION`.
- Implement `accept` feature in each of the descendant classes.

```
class CONSTANT inherit EXPRESSION
...
  accept(v: VISITOR)
    do
      v.visit_constant(Current)
    end
end
```

```
class ADDITION
inherit EXPRESSION COMPOSITE
...
  accept(v: VISITOR)
    do
      v.visit_addition(Current)
    end
end
```


Visitor Pattern Implementation: Operations

Cluster ***expression_operations***

- For each descendant class `C` of `EXPRESSION`, declare a *deferred* feature `visit_c (e: C)` in the *deferred* class `VISITOR`.

```
deferred class VISITOR
  visit_constant(c: CONSTANT) deferred end
  visit_addition(a: ADDITION) deferred end
end
```

- Each descendant of `VISITOR` denotes a kind of operation.

```
class EVALUATOR inherit VISITOR
  value : INTEGER
  visit_constant(c: CONSTANT)  do value := c.value end
  visit_addition(a: ADDITION)
    local eval_left, eval_right: EVALUATOR
    do a.left.accept(eval_left)
       a.right.accept(eval_right)
       value := eval_left.value + eval_right.value
    end
end
```

Testing the Visitor Pattern

```
1  test_expression_evaluation: BOOLEAN
2   local add, c1, c2: EXPRESSION ; v: VISITOR
3   do
4    create {CONSTANT} c1.make (1) ; create {CONSTANT} c2.make (2)
5    create {ADDITION} add.make (c1, c2)
6    create {EVALUATOR} v.make
7    add.accept(v)
8    check attached {EVALUATOR} v as eval then
9     Result := eval.value = 3
10   end
11  end
```

Double Dispatch in **Line 7**:

1. ***DT*** of `add` is *ADDITION* ⇒ Call `accept` in *ADDITION*

   `v.visit_addition (add)`

2. ***DT*** of `v` is *EVALUATOR* ⇒ Call `visit_addition` in *EVALUATOR*

   visiting result of `add.left` + visiting result of `add.right`

To Use or Not to Use the Visitor Pattern

- In the architecture of visitor pattern, what kind of *extensions* is easy and hard? Language structure? Language Operation?
  - Adding a new kind of ***operation*** element is easy.

    To introduce a new operation for generating C code, we only need to introduce a new descendant class `C_CODE_GENERATOR` of `VISITOR`, then implement how to handle each language element in that class.

    ⇒ *Single Choice Principle* is *obeyed*.
  - Adding a new kind of ***structure*** element is hard.

    After adding a descendant class `MULTIPLICATION` of `EXPRESSION`, every concrete visitor (i.e., descendant of `VISITOR`) must be amended to provide a new `visit_multiplication` operation.

    ⇒ *Single Choice Principle* is *violated*.
- The applicability of the visitor pattern depends on to what extent the ***structure*** will change.

  ⇒ Use visitor if ***operations*** applied to ***structure*** change often.

  ⇒ Do not use visitor if the ***structure*** change often.

Beyond this Lecture. . .

Learn about implementing the Composite and Visitor Patterns, from scratch, in this tutorial series:

`https://www.youtube.com/playlist?list=PL5dxAmCmjv_4z5eXGW-ZBgsS2WZTyBHY2`

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Subcontracting

Readings: OOSCS2 Chapters 14 – 16

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Aspects of Inheritance

- ***Code Reuse***
- Substitutability
  - ***Polymorphism*** and ***Dynamic Binding*** [compile-time type checks]
  - *Sub-contracting* [runtime behaviour checks]

Background of Logic (1)

Given *preconditions* P_1 and P_2, we say that

P_2 ***requires less*** than P_1 if

P_2 is ***less strict*** on (thus ***allowing more***) inputs than P_1 does.

$$\{ x \mid P_1(x) \} \subseteq \{ x \mid P_2(x) \}$$

More concisely:

$$P_1 \Rightarrow P_2$$

e.g., For command `withdraw(amount: amount)`,
$P_2 : amount \geq 0$ ***requires less*** than $P_1 : amount > 0$

What is the *precondition* that ***requires the least***? [***true***]

Background of Logic (2)

Given *postconditions* or *invariants* Q_1 and Q_2, we say that

Q_2 ***ensures more*** than Q_1 if

Q_2 is ***stricter*** on (thus ***allowing less***) outputs than Q_1 does.

$$\{ x \mid Q_2(x) \} \subseteq \{ x \mid Q_1(x) \}$$

More concisely:

$$Q_2 \Rightarrow Q_1$$

e.g., For query `q(i: INTEGER): BOOLEAN`,
$Q_2 : \texttt{Result} = (i > 0) \wedge (i \textbf{ mod } 2 = 0)$ ***ensures more*** than
$Q_1 : \texttt{Result} = (i > 0) \vee (i \textbf{ mod } 2 = 0)$

What is the *postcondition* that ***ensures the most***? [***false***]

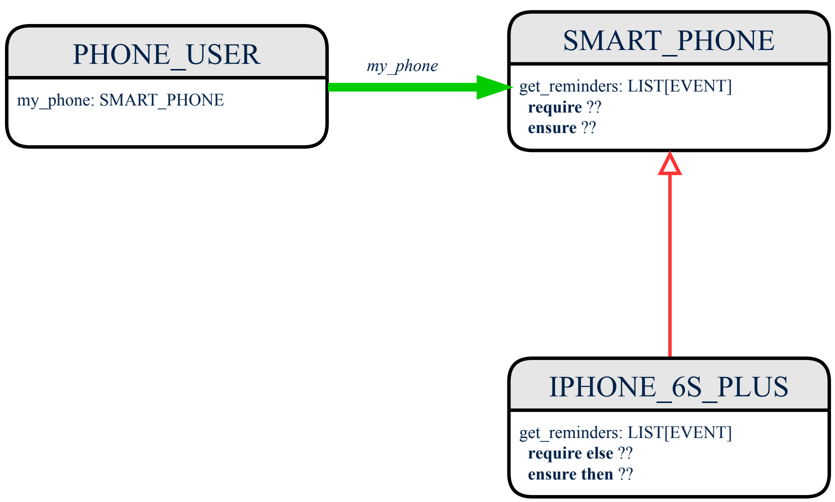
Inheritance and Contracts (1)

- The fact that we allow *polymorphism* :

```
local my_phone: SMART_PHONE
      i_phone: IPHONE_6S_PLUS
      samsung_phone: GALAXY_S6_EDGE
      htc_phone: HTC_ONE_A9
do my_phone := i_phone
   my_phone := samsung_phone
   my_phone := htc_phone
```

  suggests that these instances may *substitute* for each other.
- Intuitively, when expecting SMART_PHONE, we can substitute it by instances of any of its **descendant** classes.
  ∵ Descendants *accumulate code* from its ancestors and can thus *meet expectations* on their ancestors.
- Such *substitutability* can be reflected on contracts, where a *substitutable instance* will:
  - ***Not*** require more from clients for using the services.
  - ***Not*** ensure less to clients for using the services.

Inheritance and Contracts (2.1)



Inheritance and Contracts (2.2)

```
class SMART_PHONE
  get_reminders: LIST[EVENT]
    require
      α: battery_level ≥ 0.1 -- 10%
    ensure
      β: ∀e : Result | e happens today
end
```

```
class IPHONE_6S_PLUS
inherit SMART_PHONE redefine get_reminders end
  get_reminders: LIST[EVENT]
    require else
      γ: battery_level ≥ 0.15 -- 15%
    ensure then
      δ: ∀e : Result | e happens today or tomorrow
end
```

Contracts in descendant class IPHONE_6S_PLUS are *not suitable*.
(*battery_level* ≥ 0.1 ⇒ *battery_level* ≥ 0.15) is not a tautology.
e.g., A client able to get reminders on a SMART_PHONE, when battery level is 12%, will fail to do so on an IPHONE_6S_PLUS.

Inheritance and Contracts (2.3)

```
class SMART_PHONE
  get_reminders: LIST[EVENT]
    require
      α: battery_level ≥ 0.1 -- 10%
    ensure
      β: ∀e : Result | e happens today
end
```

```
class IPHONE_6S_PLUS
inherit SMART_PHONE redefine get_reminders end
  get_reminders: LIST[EVENT]
    require else
      γ: battery_level ≥ 0.15 -- 15%
    ensure then
      δ: ∀e : Result | e happens today or tomorrow
end
```

Contracts in descendant class IPHONE_6S_PLUS are *not suitable*.
(*e* happens ty. or tw.) ⇒ (*e* happens ty.) not tautology.
e.g., A client receiving today's reminders from SMART_PHONE are shocked by tomorrow-only reminders from IPHONE_6S_PLUS.

Inheritance and Contracts (2.4)

```
class SMART_PHONE
  get_reminders: LIST[EVENT]
    require
      α: battery_level ≥ 0.1 -- 10%
    ensure
      β: ∀e:Result | e happens today
end
```

```
class IPHONE_6S_PLUS
inherit SMART_PHONE redefine get_reminders end
  get_reminders: LIST[EVENT]
    require else
      γ: battery_level ≥ 0.05 -- 5%
    ensure then
      δ: ∀e:Result | e happens today between 9am and 5pm
end
```

Contracts in descendant class IPHONE_6S_PLUS are *suitable*.

- ***Require the same or less*** $\alpha \Rightarrow \gamma$
  Clients satisfying the precondition for SMART_PHONE are ***not*** shocked by not being to use the same feature for IPHONE_6S_PLUS.

Inheritance and Contracts (2.5)

```
class SMART_PHONE
  get_reminders: LIST[EVENT]
    require
      α: battery_level ≥ 0.1 -- 10%
    ensure
      β: ∀e:Result | e happens today
end
```

```
class IPHONE_6S_PLUS
inherit SMART_PHONE redefine get_reminders end
  get_reminders: LIST[EVENT]
    require else
      γ: battery_level ≥ 0.05 -- 5%
    ensure then
      δ: ∀e:Result | e happens today between 9am and 5pm
end
```

Contracts in descendant class IPHONE_6S_PLUS are *suitable*.

- ***Ensure the same or more*** $\delta \Rightarrow \beta$
  Clients benefiting from SMART_PHONE are ***not*** shocked by failing to gain at least those benefits from same feature in IPHONE_6S_PLUS.

Contract Redeclaration Rule (1)

- In the context of some feature in a descendant class:
  - Use `require else` to redeclare its precondition.
  - Use `ensure then` to redeclare its precondition.
- The resulting *runtime assertions checks* are:
  - `original_pre or else new_pre`

    ⇒ Clients ***able to satisfy*** *original_pre* will not be shocked.
    ∵ ***true*** ∨ *new_pre* ≡ ***true***
    A *precondition violation* will ***not*** occur as long as clients are able to satisfy what is required from the ancestor classes.
  - `original_post and then new_post`

    ⇒ ***Failing to gain*** *original_post* will be reported as an issue.
    ∵ ***false*** ∧ *new_post* ≡ ***false***
    A *postcondition violation* occurs (as expected) if clients do not receive at least those benefits promised from the ancestor classes.

Contract Redeclaration Rule (2.1)

```
class FOO
  f
    do ...
    end
end
```

```
class BAR
inherit FOO redefine f end
  f require else new_pre
    do ...
    end
end
```

- Unspecified *original_pre* is as if declaring `require true`

  ∵ ***true*** ∨ *new_pre* ≡ ***true***

```
class FOO
  f
    do ...
    end
end
```

```
class BAR
inherit FOO redefine f end
  f
    do ...
    ensure then new_post
    end
end
```

- Unspecified *original_post* is as if declaring `ensure true`

  ∵ ***true*** ∧ *new_post* ≡ *new_post*

Contract Redeclaration Rule (2.2)

```
class FOO
  f require
      original_pre
    do ...
    end
end
```

```
class BAR
inherit FOO redefine f end
  f
    do ...
    end
end
```

- Unspecified *new_pre* is as if declaring `require else false`

  $\because$ *original_pre* $\vee$ ***false*** $\equiv$ *original_pre*

```
class FOO
  f
    do ...
    ensure
      original_post
    end
end
```

```
class BAR
inherit FOO redefine f end
  f
    do ...
    end
end
```

- Unspecified *new_post* is as if declaring `ensure then true`

  $\because$ *original_post* $\wedge$ ***true*** $\equiv$ *original_post*

Invariant Accumulation

- Every class inherits *invariants* from all its ancestor classes.
- Since invariants are like postconditions of all features, they are "***conjoined***" to be checked at runtime.

```
class POLYGON
  vertices: ARRAY[POINT]
invariant
  vertices.count ≥ 3
end
```

```
class RECTANGLE
inherit POLYGON
invariant
  vertices.count = 4
end
```

- What is checked on a RECTANGLE instance at runtime:

  $(vertices.count \geq 3) \wedge (vertices.count = 4) \equiv (vertices.count = 4)$
- Can PENTAGON be a descendant class of RECTANGLE?

  $(vertices.count = 5) \wedge (vertices.count = 4) \equiv$ ***false***

Inheritance and Contracts (3)

```
class FOO
  f
    require
      original_pre
    ensure
      original_post
    end
end
```

```
class BAR
inherit FOO redefine f end
  f
    require else
      new_pre
    ensure then
      new_post
    end
end
```

(Static) ***Design Time*** :
- ***original_pre*** $\Rightarrow$ ***new_pre*** should be proved as a tautology
- ***new_post*** $\Rightarrow$ ***original_post*** should be proved as a tautology

(Dynamic) ***Runtime*** :
- ***original_pre*** $\vee$ ***new_pre*** is checked
- ***original_post*** $\wedge$ ***new_post*** is checked

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The State Design Pattern

Readings: OOSC2 Chapter 20

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Motivating Problem

Consider the reservation panel of an online booking system:

-- Enquiry on Flights --

Flight sought from: Toronto To: Zurich

Departure on or after: 23 June On or before: 24 June

Preferred airline (s):

Special requirements:

AVAILABLE FLIGHTS: 1

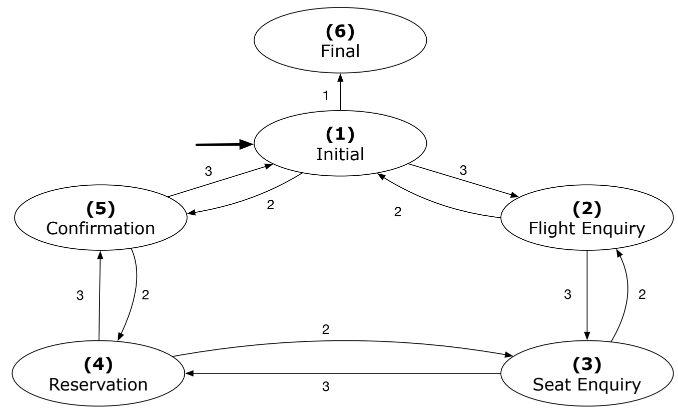
Flt#AA 42 Dep 8:25 Arr 7:45 Thru: Chicago

Choose next action:

0 – Exit
1 – Help
2 – Further enquiry
3 – Reserve a seat

State Transition Diagram

Characterize *interactive system* as: **1)** A set of *states*; and **2)** For each state, its list of *applicable transitions* (i.e., actions).
e.g., Above reservation system as a *finite state machine*:



Design Challenges

1. The state-transition graph may *large* and *sophisticated*.
   A large number N of states has $O(N^2)$ transitions
2. The graph structure is subject to *extensions*/*modifications*.
   e.g., To merge "(2) Flight Enquiry" and "(3) Seat Enquiry":
      Delete the state "(3) Seat Enquiry".
      Delete its 4 incoming/outgoing transitions.
   e.g., Add a new state "Dietary Requirements"
3. A *general solution* is needed for such *interactive systems*.
   e.g., taobao, eBay, amazon, etc.

A First Attempt

```
1_Initial_panel:
  -- Actions for Label 1.
2_Flight_Enquiry_panel:
  -- Actions for Label 2.
3_Seat_Enquiry_panel:
  -- Actions for Label 3.
4_Reservation_panel:
  -- Actions for Label 4.
5_Confirmation_panel:
  -- Actions for Label 5.
6_Final_panel:
  -- Actions for Label 6.
```

```
3_Seat_Enquiry_panel:
from
  Display Seat Enquiry Panel
until
  not (wrong answer or wrong choice)
do
  Read user's answer for current panel
  Read user's choice C for next step
  if wrong answer or wrong choice then
    Output error messages
  end
end
Process user's answer
case C in
  2: goto 2_Flight_Enquiry_panel
  3: goto 4_Reservation_panel
end
```


A First Attempt: Good Design?

- Runtime execution ≈ a ***"bowl of spaghetti"***.

  ⇒ The system's behaviour is hard to predict, trace, and debug.
- *Transitions* hardwired as system's ***central control structure***.

  ⇒ The system is vulnerable to changes/additions of states/transitions.
- All labelled blocks are largely similar in their code structures.

  ⇒ This design "***smells***" due to duplicates/repetitions!
- The branching structure of the design exactly corresponds to that of the specific *transition graph*.

  ⇒ The design is ***application-specific*** and *not reusable* for other interactive systems.

A Top-Down, Hierarchical Solution

- *Separation of Concern* Declare the *transition table* as a feature the system, rather than its central control structure:

```
transition (src: INTEGER; choice: INTEGER): INTEGER
    -- Return state by taking transition 'choice' from 'src' state.
  require valid_source_state: 1 ≤ src ≤ 6
          valid_choice: 1 ≤ choice ≤ 3
  ensure valid_target_state: 1 ≤ Result ≤ 6
```

- We may implement `transition` via a 2-D array.

Src State \ Choice	1	2	3
1 (Initial)	6	5	2
2 (Flight Enquiry)	–	1	3
3 (Seat Enquiry)	–	2	4
4 (Reservation)	–	3	5
5 (Confirmation)	–	4	1
6 (Final)	–	–	–

state \ choice	1	2	3
1	6	5	2
2		1	3
3		2	4
4		3	5
5		4	1
6			

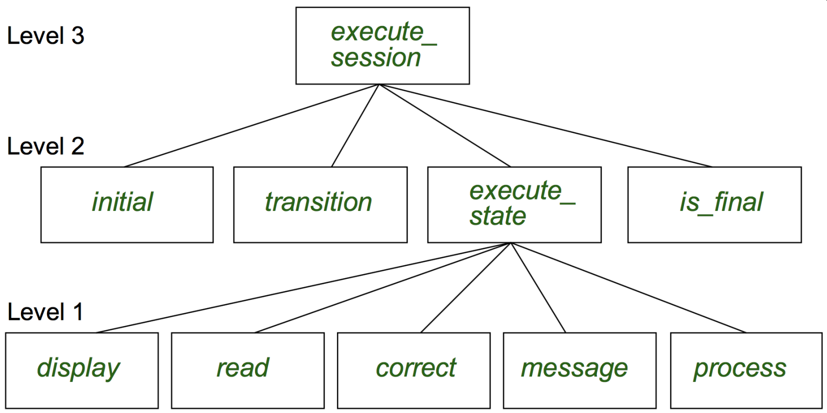
Hierarchical Solution: Good Design?

- This is a more general solution.

  ∵ *State transitions* are *separated* from the system's *central control structure*.

  ⇒ *Reusable* for another interactive system by making changes only to the `transition` feature.
- How does the *central control structure* look like in this design?

Hierarchical Solution: Top-Down Functional Decomposition



Modules of **execute_session** and **execute_state** are general enough on their *control structures*. ⇒ *reusable*

Hierarchical Solution: System Control

All interactive sessions **share** the following *control pattern*:

- Start with some *initial state*.
- Repeatedly make *state transitions* (based on *choices* read from the user) until the state is *final* (i.e., the user wants to exit).

```
execute_session
  -- Execute a full interactive session.
 local
  current_state , choice: INTEGER
 do
  from
   current_state := initial
  until
   is_final (current_state)
  do
   choice := execute_state ( current_state )
   current_state := transition (current_state, choice)
  end
 end
```


Hierarchical Solution: State Handling (1)

The following *control pattern* handles **all** states:

```
execute_state ( current_state : INTEGER): INTEGER
  -- Handle interaction at the current state.
  -- Return user's exit choice.
 local
  answer: ANSWER; valid_answer: BOOLEAN; choice: INTEGER
 do
  from
  until
   valid_answer
  do
   display( current_state )
   answer := read_answer( current_state )
   choice := read_choice( current_state )
   valid_answer := correct( current_state , answer)
   if not valid_answer then message( current_state , answer)
  end
  process( current_state , answer)
  Result := choice
 end
```


Hierarchical Solution: State Handling (2)

FEATURE CALL	FUNCTIONALITY
display(s)	Display screen outputs associated with ***state*** *s*
read_answer(s)	Read user's input for answers associated with ***state*** *s*
read_choice(s)	Read user's input for exit choice associated with ***state*** *s*
correct(s, answer)	Is the user's *answer* valid w.r.t. ***state*** *s*?
process(s, answer)	Given that user's *answer* is valid w.r.t. ***state*** *s*, process it accordingly.
message(s, answer)	Given that user's *answer* is not valid w.r.t. ***state*** *s*, display an error message accordingly.

Q: How similar are the code structures of the above state-dependant commands or queries?

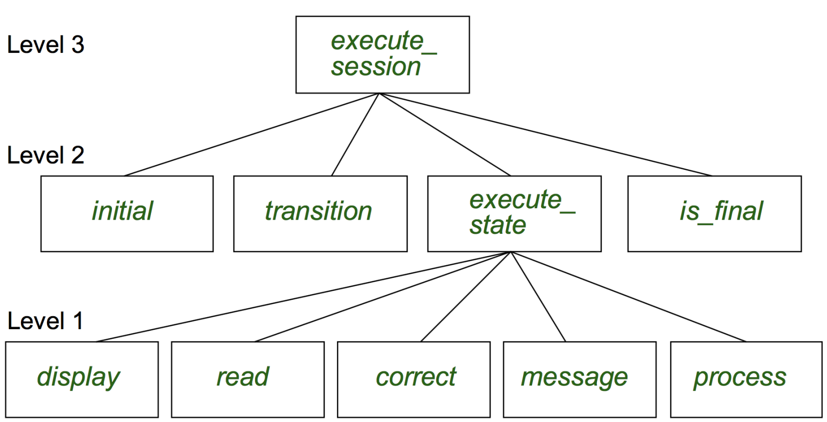
Hierarchical Solution: State Handling (3)

A: Actions of all such state-dependant features must **explicitly** *discriminate* on the input state argument.

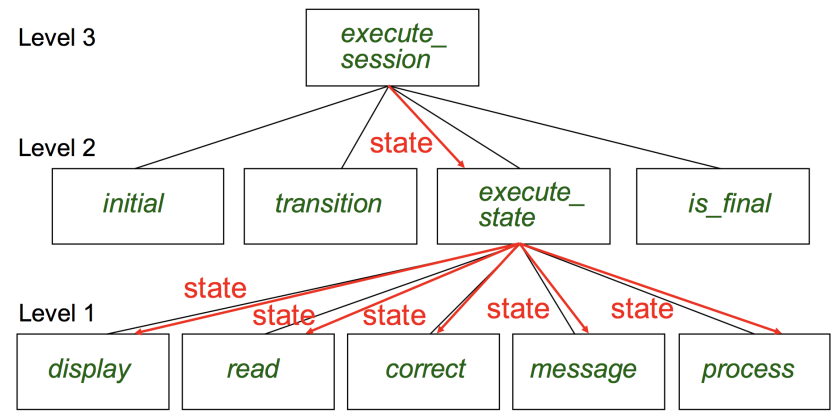
```
display(current_state: INTEGER)
 require
  valid_state: 1 ≤ current_state ≤ 6
 do
  if current_state = 1 then
   -- Display Initial Panel
  elseif current_state = 2 then
   -- Display Flight Enquiry Panel
  ...
  else
   -- Display Final Panel
  end
 end
```

- Such design *smells* !
  ∵ Same list of conditional repeats for **all** state-dependant features.
- Such design ***violates*** the *Single Choice Principle* .
  e.g., To add/delete a state ⇒ Add/delete a branch in all such features.

Hierarchical Solution: Visible Architecture



Hierarchical Solution: Pervasive States



Too much data transmission: `current_state` is passed
- From `execute_session` (**Level 3**) to `execute_state` (**Level 2**)
- From `execute_state` (**Level 2**) to all features at **Level 1**

Law of Inversion

If your routines exchange too many data, then put your routines in your data.

e.g.,

`execute_state` (**Level 2**) and all features at **Level 1**:

- Pass around (as ***inputs***) the notion of ***current_state***
- Build upon (via ***discriminations***) the notion of ***current_state***

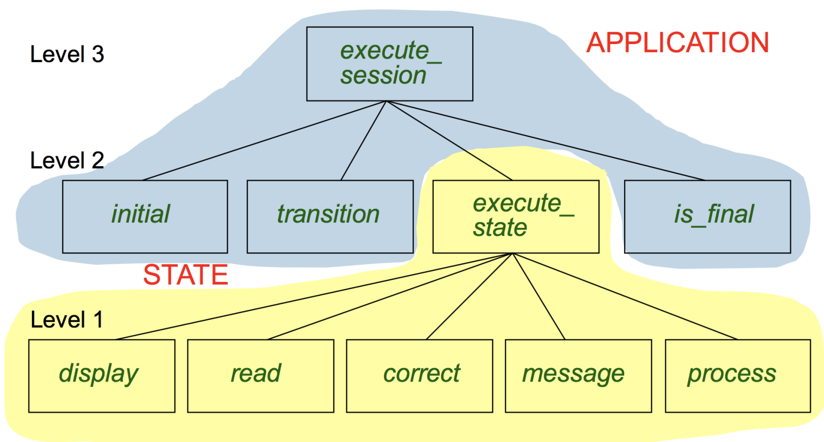
execute_state	(*s: INTEGER*)
display	(*s: INTEGER*)
read_answer	(*s: INTEGER*)
read_choice	(*s: INTEGER*)
correct	(*s: INTEGER* ; answer: ANSWER)
process	(*s: INTEGER* ; answer: ANSWER)
message	(*s: INTEGER* ; answer: ANSWER)

⇒ *Modularize* the notion of state as ***class STATE***.

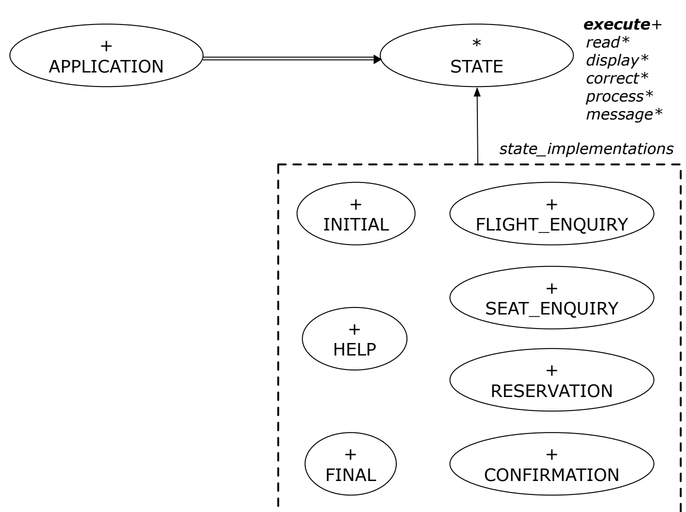
⇒ *Encapsulate* state-related information via a ***STATE*** interface.

⇒ Notion of ***current_state*** becomes ***implicit***: the `Current` class.

Grouping by Data Abstractions



Architecture of the State Pattern



The STATE ADT

```
deferred class STATE
  read
    -- Read user's inputs
    -- Set 'answer' and 'choice'
   deferred end
  answer: ANSWER
    -- Answer for current state
  choice: INTEGER
    -- Choice for next step
  display
    -- Display current state
   deferred end
  correct: BOOLEAN
   deferred end
  process
   require correct
   deferred end
  message
   require not correct
   deferred end
```

```
  execute
   local
    good: BOOLEAN
   do
    from
    until
     good
    loop
     display
     -- set answer and choice
     read
     good := correct
     if not good then
      message
     end
    end
    process
  end
end
```


The Template Design Pattern

Consider the following fragment of Eiffel code:

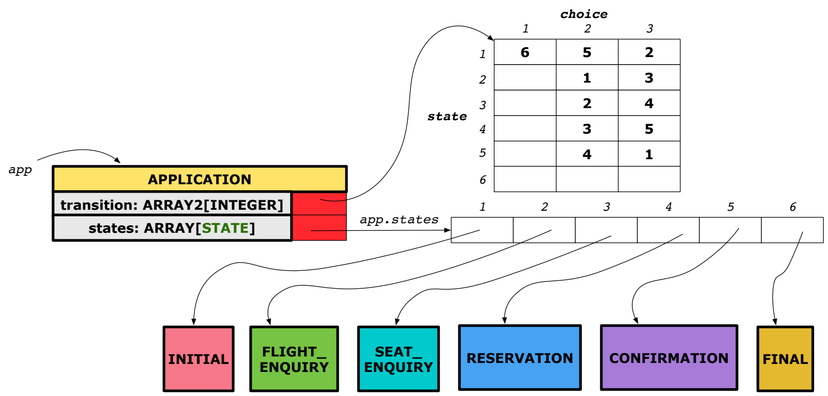
```
1  s: STATE
2  create {SEAT_ENQUIRY} s.make
3  s.execute
4  create {CONFIRMATION} s.make
5  s.execute
```

L2 and **L4**: the same version of effective feature `execute` (from the deferred class ***STATE***) is called. [*template*]

L2: specific version of effective features `display`, `process`, *etc.*, (from the effective descendant class ***SEAT_ENQUIRY***) is called. [*template instantiated for **SEAT_ENQUIRY***]

L4: specific version of effective features `display`, `process`, *etc.*, (from the effective descendant class ***CONFIRMATION***) is called. [*template instantiated for **CONFIRMATION***]

APPLICATION Class: Array of STATE



	1	2	3
1	6	5	2
2		1	3
3		2	4
4		3	5
5		4	1
6			

APPLICATION Class (1)

```
class APPLICATION create make
feature {NONE} -- Implementation of Transition Graph
  transition: ARRAY2[INTEGER]
    -- State transitions: transition[state, choice]
  states: ARRAY[STATE]
    -- State for each index, constrained by size of 'transition'
feature
  initial: INTEGER
  number_of_states: INTEGER
  number_of_choices: INTEGER
  make(n, m: INTEGER)
    do number_of_states := n
       number_of_choices := m
       create transition.make_filled(0, n, m)
       create states.make_empty
    end
invariant
  transition.height = number_of_states
  transition.width = number_of_choices
end
```


APPLICATION Class (2)

```
class APPLICATION
feature {NONE} -- Implementation of Transition Graph
  transition: ARRAY2[INTEGER]
  states: ARRAY[STATE]
feature
  put_state(s: STATE; index: INTEGER)
    require 1 ≤ index ≤ number_of_states
    do states.force(s, index) end
  choose_initial(index: INTEGER)
    require 1 ≤ index ≤ number_of_states
    do initial := index end
  put_transition(tar, src, choice: INTEGER)
    require
      1 ≤ src ≤ number_of_states
      1 ≤ tar ≤ number_of_states
      1 ≤ choice ≤ number_of_choices
    do
      transition.put(tar, src, choice)
    end
end
```


Example Test: Non-Interactive Session

```
test_application: BOOLEAN
  local
    app: APPLICATION ; current_state: STATE ; index: INTEGER
  do
    create app.make (6, 3)
    app.put_state (create {INITIAL}.make, 1)
    -- Similarly for other 5 states.
    app.choose_initial (1)
    -- Transit to FINAL given current state INITIAL and choice 1.
    app.put_transition (6, 1, 1)
    -- Similarly for other 10 transitions.

    index := app.initial
    current_state := app.states [index]
    Result := attached {INITIAL} current_state
    check Result end
    -- Say user's choice is 3: transit from INITIAL to FLIGHT_STATUS
    index := app.transition.item (index, 3)
    current_state := app.states [index]
    Result := attached {FLIGHT_ENQUIRY} current_state
end
```

APPLICATION Class (3): Interactive Session

```
class APPLICATION
feature {NONE} -- Implementation of Transition Graph
  transition: ARRAY2[INTEGER]
  states: ARRAY[STATE]
feature
  execute_session
    local
      current_state: STATE
      index: INTEGER
    do
      from
        index := initial
      until
        is_final (index)
      loop
        current_state := states[index] -- polymorphism
        current_state.execute -- dynamic binding
        index := transition.item (index, current_state.choice)
      end
    end
end
```


Building an Application

- Create instances of `STATE`.

```
s1: STATE
create {INITIAL} s1.make
```

- Initialize an `APPLICATION`.

```
create app.make(number_of_states, number_of_choices)
```

- Perform polymorphic assignments on `app.states`.

```
app.put_state(initial, 1)
```

- Choose an initial state.

```
app.choose_initial(1)
```

- Build the transition table.

```
app.put_transition(6, 1, 1)
```

- Run the application.

```
app.execute_session
```


Top-Down, Hierarchical vs. OO Solutions

- In the second (top-down, hierarchy) solution, it is required for every state-related feature to *explicitly* and *manually* discriminate on the argument value, via a a list of conditionals.
  e.g., Given `display(current_state: INTEGER)`, the calls display(1) and display(2) behave differently.
- The third (OO) solution, called the State Pattern, makes such conditional *implicit* and *automatic*, by making `STATE` as a deferred class (whose descendants represent all types of states), and by delegating such conditional actions to *dynamic binding*.
  e.g., Given `s: STATE`, behaviour of the call s.display depends on the *dynamic type* of `s` (such as `INITIAL` vs. `FLIGHT_ENQUIRY`).

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Observer Design Pattern
Event-Driven Design

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

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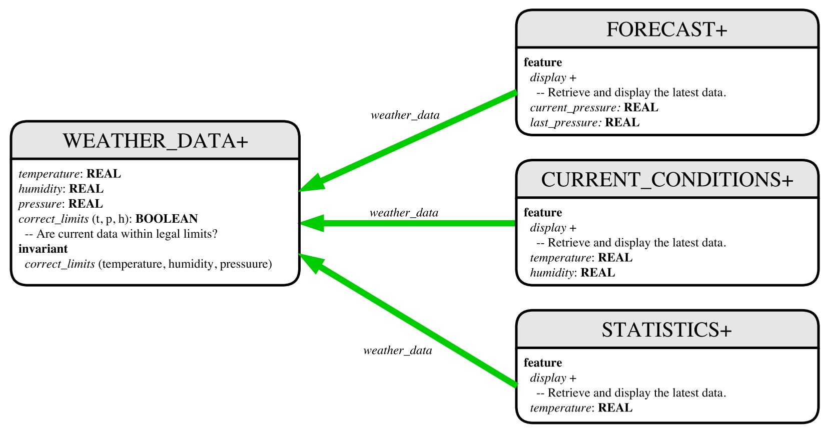
Motivating Problem

- A *weather station* maintains *weather data* such as *temperature*, *humidity*, and *pressure*.
- Various kinds of applications on these *weather data* should regularly update their *displays*:
  - *Condition*: *temperature* in celsius and *humidity* in percentages.
  - *Forecast*: if expecting for rainy weather due to reduced *pressure*.
  - *Statistics*: minimum/maximum/average measures of *temperature*.

First Design: Weather Station



Whenever the `display` feature is called, **retrieve** the current values of `temperature`, `humidity`, and/or `pressure` via the `weather_data` reference.

Implementing the First Design (1)

```
class WEATHER_DATA create make
feature -- Data
  temperature: REAL
  humidity: REAL
  pressure: REAL
feature -- Queries
  correct_limits(t,p,h: REAL): BOOLEAN
    ensure
      Result implies -36 <=t and t <= 60
      Result implies 50 <= p and p <= 110
      Result implies 0.8 <= h and h <= 100
feature -- Commands
  make (t, p, h: REAL)
    require
      correct_limits(temperature, pressure, humidity)
    ensure
      temperature = t and pressure = p and humidity = h
invariant
  correct_limits(temperature, pressure, humidity)
end
```


Implementing the First Design (2.1)

```
class FORECAST create make
feature -- Attributes
  current_pressure: REAL
  last_pressure: REAL
  weather_data: WEATHER_DATA
feature -- Commands
  make(wd: WEATHER_DATA)
    ensure weather_data = wd
  update
    do last_pressure := current_pressure
       current_pressure := weather_data.pressure
    end
  display
    do update
       if current_pressure > last_pressure then
         print("Improving weather on the way!%N")
       elseif current_pressure = last_pressure then
         print("More of the same%N")
       else print("Watch out for cooler, rainy weather%N") end
    end
end
```


Implementing the First Design (2.2)

```
class CURRENT_CONDITIONS create make
feature -- Attributes
  temperature: REAL
  humidity: REAL
  weather_data: WEATHER_DATA
feature -- Commands
  make(wd: WEATHER_DATA)
    ensure weather_data = wd
  update
    do temperature := weather_data.temperature
       humidity := weather_data.humidity
    end
  display
    do update
       io.put_string("Current Conditions: ")
       io.put_real (temperature) ; io.put_string (" degrees C and ")
       io.put_real (humidity) ; io.put_string (" percent humidity%N")
    end
end
```


Implementing the First Design (2.3)

```
class STATISTICS create make
feature -- Attributes
  weather_data: WEATHER_DATA
  current_temp: REAL
  max, min, sum_so_far: REAL
  num_readings: INTEGER
feature -- Commands
  make(wd: WEATHER_DATA)
    ensure weather_data = wd
  update
    do current_temp := weather_data.temperature
       -- Update min, max if necessary.
    end
  display
    do update
       print("Avg/Max/Min temperature = ")
       print(sum_so_far / num_readings + "/" + max + "/" min + "%N")
    end
end
```

Implementing the First Design (3)

```
1  class WEATHER_STATION create make
2  feature -- Attributes
3    cc: CURRENT_CONDITIONS ; fd: FORECAST ; sd: STATISTICS
4    wd: WEATHER_DATA
5  feature -- Commands
6    make
7      do create wd.make (9, 75, 25)
8         create cc.make (wd) ; create fd.make (wd) ; create sd.make(wd)
9
10        wd.set_measurements (15, 60, 30.4)
11        cc.display ; fd.display ; sd.display
12        cc.display ; fd.display ; sd.display
13
14        wd.set_measurements (11, 90, 20)
15        cc.display ; fd.display ; sd.display
16   end
17 end
```

L14: Updates occur on `cc`, `fd`, `sd` even with the same data.

First Design: Good Design?

- Each application (`CURRENT_CONDITION`, `FORECAST`, `STATISTICS`) *cannot know* when the weather data change.

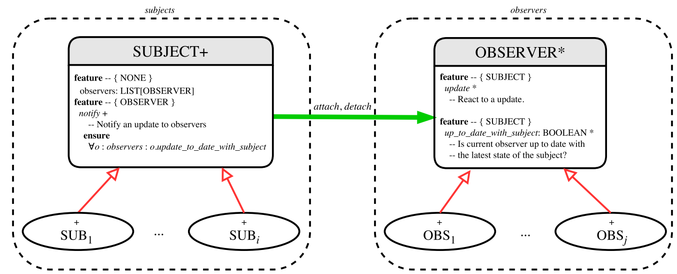
  ⇒ All applications have to periodically initiate updates in order to keep the `display` results up to date.

  ∵ Each inquiry of current weather data values is *a remote call*.

  ∴ Waste of computing resources (e.g., network bandwidth) when there are actually no changes on the weather data.
- To avoid such overhead, it is better to let:
  - Each application is ***subscribed/attached/registered*** to the weather data.
  - The weather station ***publish/notify*** new changes.

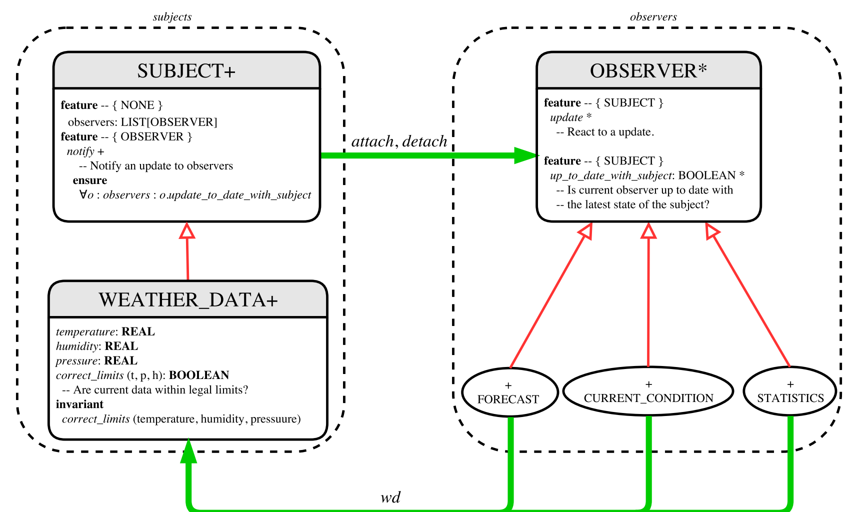
    ⇒ Updates on the application side occur only *when necessary*.

Observer Pattern: Architecture



- Observer (publish-subscribe) pattern: *one-to-many* relation.
  - Observers (*subscribers*) are attached to a subject (*publisher*).
  - The subject notify its attached observers about changes.
- Some interchangeable vocabulary:
  - subscribe ≈ attach ≈ register
  - unsubscribe ≈ detach ≈ unregister
  - publish ≈ notify
  - handle ≈ update

Observer Pattern: Weather Station



Implementing the Observer Pattern (1.1)

```
class SUBJECT create make
feature -- Attributes
  observers : LIST[OBSERVER]
feature -- Commands
  make
   do create {LINKED_LIST[OBSERVER]} observers.make
   ensure no_observers: observers.count = 0 end
feature -- Invoked by an OBSERVER
  attach (o: OBSERVER) -- Add 'o' to the observers
    require not_yet_attached: not observers.has (o)
    ensure is_attached: observers.has (o) end
  detach (o: OBSERVER) -- Add 'o' to the observers
    require currently_attached: observers.has (o)
    ensure is_attached: not observers.has (o) end
feature -- invoked by a SUBJECT
  notify -- Notify each attached observer about the update.
    do across observers as cursor loop cursor.item.update end
    ensure all_views_updated:
      across observers as o all o.item.up_to_date_with_subject end
    end
end
```


Implementing the Observer Pattern (1.2)

```
class WEATHER_DATA
inherit SUBJECT  rename make as make_subject end
create make
feature -- data available to observers
  temperature: REAL
  humidity: REAL
  pressure: REAL
  correct_limits(t,p,h: REAL): BOOLEAN
feature -- Initialization
  make (t, p, h: REAL)
    do
      make_subject -- initialize empty observers
      set_measurements (t, p, h)
    end
feature -- Called by weather station
  set_measurements(t, p, h: REAL)
    require correct_limits(t,p,h)
invariant
  correct_limits(temperature, pressure, humidity)
end
```


Implementing the Observer Pattern (2.1)

```
deferred class
  OBSERVER
feature -- To be effected by a descendant
  up_to_date_with_subject: BOOLEAN
      -- Is this observer up to date with its subject?
    deferred
    end

  update
      -- Update the observer's view of 's'
    deferred
    ensure
      up_to_date_with_subject: up_to_date_with_subject
    end
end
```

Each effective descendant class of `OBSERVER` should:

- Define what weather data are required to be up-to-date.
- Define how to update the required weather data.

Implementing the Observer Pattern (2.2)

```
class FORECAST
inherit OBSERVER
feature -- Commands
  make(a_weather_data: WEATHER_DATA)
    do weather_data := a_weather_data
       weather_data.attach (Current)
    ensure weather_data = a_weather_data
           weather_data.observers.has (Current)
    end
feature -- Queries
  up_to_date_with_subject: BOOLEAN
    ensure then
      Result = current_pressure = weather_data.pressure
  update
    do -- Same as 1st design; Called only on demand
    end
  display
    do -- No need to update; Display contents same as in 1st design
    end
end
```

Implementing the Observer Pattern (2.3)

```
class CURRENT_CONDITIONS
inherit OBSERVER
feature -- Commands
  make(a_weather_data: WEATHER_DATA)
    do weather_data := a_weather_data
       weather_data.attach (Current)
    ensure weather_data = a_weather_data
           weather_data.observers.has (Current)
    end
feature -- Queries
  up_to_date_with_subject: BOOLEAN
    ensure then Result = temperature = weather_data.temperature and
                          humidity = weather_data.humidity
  update
    do -- Same as 1st design; Called only on demand
    end
  display
    do -- No need to update; Display contents same as in 1st design
    end
end
```


Implementing the Observer Pattern (2.4)

```
class STATISTICS
inherit OBSERVER
feature -- Commands
  make(a_weather_data: WEATHER_DATA)
    do weather_data := a_weather_data
       weather_data.attach (Current)
    ensure weather_data = a_weather_data
           weather_data.observers.has (Current)
    end
feature -- Queries
  up_to_date_with_subject: BOOLEAN
    ensure then
      Result = current_temperature = weather_data.temperature
  update
    do -- Same as 1st design; Called only on demand
    end
  display
    do -- No need to update; Display contents same as in 1st design
    end
end
```


Implementing the Observer Pattern (3)

```
1  class WEATHER_STATION create make
2  feature -- Attributes
3    cc: CURRENT_CONDITIONS ; fd: FORECAST ; sd: STATISTICS
4    wd: WEATHER_DATA
5  feature -- Commands
6    make
7      do create wd.make (9, 75, 25)
8         create cc.make (wd) ; create fd.make (wd) ; create sd.make(wd)
9
10        wd.set_measurements (15, 60, 30.4)
11        wd.notify
12        cc.display ; fd.display ; sd.display
13        cc.display ; fd.display ; sd.display
14
15        wd.set_measurements (11, 90, 20)
16        wd.notify
17        cc.display ; fd.display ; sd.display
18   end
19 end
```

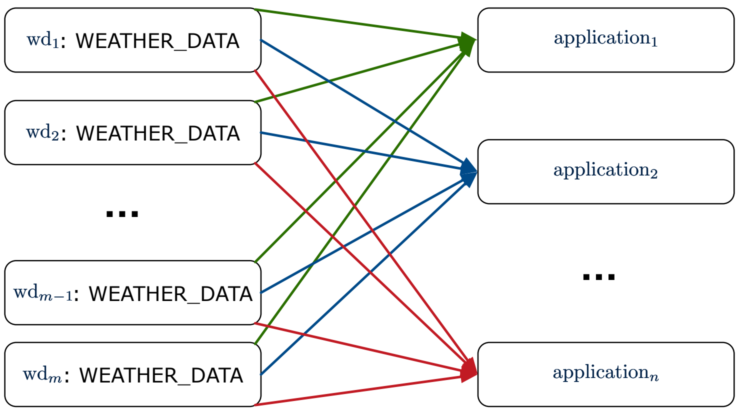
L13: `cc`, `fd`, `sd` make use of "cached" data values.

Observer Pattern: Limitation? (1)

- The *observer design pattern* is a reasonable solution to building a *one-to-many* relationship: one subject (publisher) and multiple observers (subscribers).
- But what if a *many-to-many* relationship is required for the application under development?
  - *Multiple* *weather data* are maintained by weather stations.
  - Each application observes *all* these *weather data*.
  - But, each application still stores the *latest* measure only. e.g., the statistics app stores one copy of `temperature`
  - Whenever some weather station updates the `temperature` of its associated *weather data*, all **relevant** subscribed applications (i.e., current conditions, statistics) should update their temperatures.
- How can the observer pattern solve this general problem?
  - Each *weather data* maintains a list of subscribed *applications*.
  - Each *application* is subscribed to *multiple* *weather data*.

Observer Pattern: Limitation? (2)

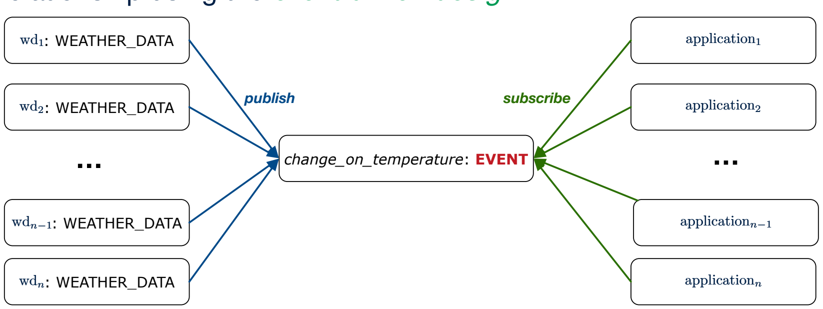
What happens at runtime when building a *many-to-many* relationship using the *observer pattern*?



Graph complexity, with m subjects and n observers? [$O(\, m \cdot n \,)$]

Event-Driven Design (1)

Here is what happens at runtime when building a *many-to-many* relationship using the *event-driven design*.



Graph complexity, with m subjects and n observers? [$O(\, m+n \,)$]

Additional cost by adding a new subject? [$O(1)$]

Additional cost by adding a new observer? [$O(1)$]

Additional cost by adding a new event type? [$O(m+n)$]

Event-Driven Design (2)

In an *event-driven design*:

- Each variable being observed (e.g., `temperature`, `humidity`, `pressure`) is called a *monitored variable*.

  e.g., A nuclear power plant (i.e., the ***subject***) has its `temperature` and `pressure` being *monitored* by a shutdown system (i.e., an ***observer***): as soon as values of these *monitored variables* exceed the normal threshold, the SDS will be notified and react by shutting down the plant.
- Each *monitored variable* is declared as an *event*:
  - An ***observer*** is ***attached***/***subscribed*** to the relevant events.
    - `CURRENT_CONDITION` attached to events for `temperature`, `humidity`.
    - `FORECAST` only subscribed to the event for `pressure`.
    - `STATISTICS` only subscribed to the event for `temperature`.
  - A ***subject*** ***notifies***/***publishes*** changes to the relevant events.

Event-Driven Design: Implementation

- Requirements for implementing an *event-driven design* are:
  1. When an ***observer*** object is *subscribed to* an ***event***, it attaches:
     - **1.1** The **reference/pointer** to an update operation
       Such reference/pointer is used for delayed executions.
     - **1.2** Itself (i.e., the **context object** for invoking the update operation)
  2. For the ***subject*** object to *publish* an update to the ***event***, it:
     - **2.1** Iterates through all its observers (or listeners)
     - **2.2** Uses the operation reference/pointer (attached earlier) to update the corresponding observer.
- Both requirements can be satisfied by Eiffel and Java.
- We will compare how an *event-driven design* for the weather station problems is implemented in Eiffel and Java.

  ⇒ It's much more convenient to do such design in Eiffel.

Event-Driven Design in Java (1)

```
1  public class Event {
2    Hashtable<Object, MethodHandle> listenersActions;
3    Event() { listenersActions = new Hashtable<>(); }
4    void subscribe(Object listener, MethodHandle action) {
5      listenersActions.put( listener , action );
6    }
7    void publish(Object arg) {
8      for (Object listener : listenersActions.keySet()) {
9        MethodHandle action = listenersActions.get(listener);
10       try {
11         action .invokeWithArguments( listener , arg);
12       } catch (Throwable e) { }
13     }
14   }
15 }
```

- **L5**: Both the delayed `action` reference and its context object (or call target) `listener` are stored into the table.
- **L11**: An invocation is made from retrieved `listener` and `action`.

Event-Driven Design in Java (2)

```
public class WeatherData {
  private double temperature;
  private double pressure;
  private double humidity;
  public WeatherData(double t, double p, double h) {
    setMeasurements(t, h, p);
  }
  public static Event changeOnTemperature = new Event();
  public static Event changeOnHumidity = new Event();
  public static Event changeOnPressure = new Event();
  public void setMeasurements(double t, double h, double p) {
    temperature = t;
    humidity = h;
    pressure = p;
    changeOnTemperature .publish(temperature);
    changeOnHumidity .publish(humidity);
    changeOnPressure .publish(pressure);
  }
}
```


Event-Driven Design in Java (3)

```
public class CurrentConditions {
  private double temperature; private double humidity;
  public void updateTemperature(double t) { temperature = t; }
  public void updateHumidity(double h) { humidity = h; }
  public CurrentConditions() {
    MethodHandles.Lookup lookup = MethodHandles.lookup();
    try {
      MethodHandle ut = lookup.findVirtual(
        this.getClass(), "updateTemperature",
        MethodType.methodType(void.class, double.class));
      WeatherData.changeOnTemperature.subscribe(this, ut);
      MethodHandle uh = lookup.findVirtual(
        this.getClass(), "updateHumidity",
        MethodType.methodType(void.class, double.class));
      WeatherData.changeOnHumidity.subscribe(this, uh);
    } catch (Exception e) { e.printStackTrace(); }
  }
  public void display() {
    System.out.println("Temperature: " + temperature);
    System.out.println("Humidity: " + humidity); } }
```


Event-Driven Design in Java (4)

```
1  public class WeatherStation {
2    public static void main(String[] args) {
3      WeatherData wd = new WeatherData(9, 75, 25);
4      CurrentConditions cc = new CurrentConditions();
5      System.out.println("=======");
6      wd.setMeasurements(15, 60, 30.4);
7      cc.display();
8      System.out.println("=======");
9      wd.setMeasurements(11, 90, 20);
10     cc.display();
11 } }
```

L4 invokes

`WeatherData.changeOnTemperature.subscribe(cc, ``updateTemperature handle'')`

L6 invokes

`WeatherData.changeOnTemperature.publish(15)`

which in turn invokes

`` ``updateTemperature handle''.invokeWithArguments(cc, 15) ``

Event-Driven Design in Eiffel (1)

```
1  class EVENT [ARGUMENTS -> TUPLE ]
2  create make
3  feature -- Initialization
4   actions: LINKED_LIST[PROCEDURE[ARGUMENTS]]
5   make do create actions.make end
6  feature
7   subscribe (an_action: PROCEDURE[ARGUMENTS])
8     require action_not_already_subscribed: not actions.has(an_action)
9     do actions.extend (an_action)
10    ensure action_subscribed: action.has(an_action) end
11  publish (args: ARGUMENTS)
12    do from actions.start until actions.after
13       loop actions.item.call (args) ; actions.forth end
14    end
15 end
```

- **L1** constrains the generic parameter `ARGUMENTS`: any class that instantiates `ARGUMENTS` must be a ***descendant*** of `TUPLE`.
- **L4**: The type ***PROCEDURE*** encapsulates both the context object and the reference/pointer to some update operation.

Event-Driven Design in Eiffel (2)

```
class WEATHER_DATA
create make
feature -- Measurements
 temperature: REAL ; humidity: REAL ; pressure: REAL
 correct_limits(t,p,h: REAL): BOOLEAN do ... end
 make (t, p, h: REAL) do ... end
feature -- Event for data changes
 change_on_temperature : EVENT[TUPLE[REAL]]once create Result end
 change_on_humidity : EVENT[TUPLE[REAL]]once create Result end
 change_on_pressure : EVENT[TUPLE[REAL]]once create Result end
feature -- Command
 set_measurements(t, p, h: REAL)
   require correct_limits(t,p,h)
   do temperature := t ; pressure := p ; humidity := h
      change_on_temperature .publish ([t])
      change_on_humidity .publish ([p])
      change_on_pressure .publish ([h])
   end
invariant correct_limits(temperature, pressure, humidity) end
```


Event-Driven Design in Eiffel (3)

```
1  class CURRENT_CONDITIONS
2  create make
3  feature -- Initialization
4   make(wd: WEATHER_DATA)
5     do
6       wd.change_on_temperature.subscribe (agent update_temperature)
7       wd.change_on_humidity.subscribe (agent update_humidity)
8     end
9  feature
10  temperature: REAL
11  humidity: REAL
12  update_temperature (t: REAL) do temperature := t end
13  update_humidity (h: REAL) do humidity := h end
14  display do ... end
15 end
```

- **agent** `cmd` retrieves the pointer to `cmd` and its context object.
- **L6** ≈ ... (**agent** ***Current***.update_temperature)
- Contrast **L6** with **L8–11** in Java class `CurrentConditions`.

Event-Driven Design in Eiffel (4)

```
1  class WEATHER_STATION create make
2  feature
3   cc: CURRENT_CONDITIONS
4   make
5     do create wd.make (9, 75, 25)
6        create cc.make (wd)
7        wd.set_measurements (15, 60, 30.4)
8        cc.display
9        wd.set_measurements (11, 90, 20)
10       cc.display
11    end
12 end
```

L6 invokes

`wd.change_on_temperature.subscribe( agent cc.update_temperature)`

L7 invokes

`wd.change_on_temperature.publish([15])`

which in turn invokes `cc.update_temperature(15)`

Event-Driven Design: Eiffel vs. Java

- *Storing observers/listeners of an event*
  - Java, in the `Event` class:

```
Hashtable<Object, MethodHandle> listenersActions;
```

  - Eiffel, in the `EVENT` class:

```
actions: LINKED_LIST[PROCEDURE[ARGUMENTS]]
```

- *Creating and passing function pointers*
  - Java, in the `CurrentConditions` class constructor:

```
MethodHandle ut = lookup.findVirtual(
  this.getClass(), "updateTemperature",
  MethodType.methodType(void.class, double.class));
WeatherData.changeOnTemperature.subscribe(this, ut);
```

  - Eiffel, in the `CURRENT_CONDITIONS` class construction:

```
wd.change_on_temperature.subscribe (agent update_temperature)
```

⇒ Eiffel's type system has been better thought-out for *design* .

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Program Correctness

OOSC2 Chapter 11

EECS3311 M: Software Design
Winter 2019

CHEN-WEI WANG

Weak vs. Strong Assertions

- Describe each assertion as ***a set of satisfying value***.
  $x > 3$ has satisfying values $\{ x \mid x > 3 \} = \{ 4, 5, 6, 7, \dots \}$
  $x > 4$ has satisfying values $\{ x \mid x > 4 \} = \{ 5, 6, 7, \dots \}$
- An assertion p is ***stronger*** than an assertion q if p's set of satisfying values is a subset of q's set of satisfying values.
  - Logically speaking, p being stronger than q (or, q being weaker than p) means $p \Rightarrow q$.
  - e.g., $x > 4 \Rightarrow x > 3$
- What's the weakest assertion? [TRUE]
- What's the strongest assertion? [FALSE]
- In *Design by Contract* :
  - A weaker *invariant* has more acceptable object states
    e.g., *balance* > 0 vs. *balance* > 100 as an invariant for ACCOUNT
  - A weaker *precondition* has more acceptable input values
  - A weaker *postcondition* has more acceptable output values

Motivating Examples (1)

Is this feature correct?

```
class FOO
  i: INTEGER
  increment_by_9
    require
      i > 3
    do
      i := i + 9
    ensure
      i > 13
    end
end
```

Q: Is $i > 3$ is too weak or too strong?

A: Too weak

∵ assertion $i > 3$ allows value 4 which would fail postcondition.

Motivating Examples (2)

Is this feature correct?

```
class FOO
  i: INTEGER
  increment_by_9
    require
      i > 5
    do
      i := i + 9
    ensure
      i > 13
    end
end
```

Q: Is $i > 5$ too weak or too strong?

A: Maybe too strong

∵ assertion $i > 5$ disallows 5 which would not fail postcondition.
Whether 5 should be allowed depends on the requirements.

Software Correctness

- Correctness is a *relative* notion:

  consistency of *implementation* with respect to *specification*.

  ⇒ This assumes there is a specification!
- We introduce a formal and systematic way for formalizing a program **S** and its *specification* (pre-condition Q and post-condition R) as a *Boolean predicate*: $\{Q\}$ **S** $\{R\}$
  - e.g., $\{i > 3\}$ `i := i + 9` $\{i > 13\}$
  - e.g., $\{i > 5\}$ `i := i + 9` $\{i > 13\}$
  - If $\{Q\}$ **S** $\{R\}$ **can** be proved **TRUE**, then the **S** is correct.

    e.g., $\{i > 5\}$ `i := i + 9` $\{i > 13\}$ can be proved TRUE.
  - If $\{Q\}$ **S** $\{R\}$ **cannot** be proved **TRUE**, then the **S** is incorrect.

    e.g., $\{i > 3\}$ `i := i + 9` $\{i > 13\}$ cannot be proved TRUE.

Hoare Logic

- Consider a program **S** with precondition Q and postcondition R.
  - $\{Q\}$ S $\{R\}$ is a *correctness predicate* for program **S**
  - $\{Q\}$ S $\{R\}$ is TRUE if program **S** starts executing in a state satisfying the precondition Q, and then:

    (a) The program **S** terminates.

    (b) Given that program **S** terminates, then it terminates in a state satisfying the postcondition R.
- Separation of concerns

  (a) requires a proof of *termination*.

  (b) requires a proof of ***partial** correctness*.

  Proofs of (a) + (b) imply ***total** correctness*.

Hoare Logic and Software Correctness

Consider the *contract view* of a feature *f* (whose body of implementation is **S**) as a Hoare Triple:

$$\{Q\}\ S\ \{R\}$$

Q is the *precondition* of *f*.
S is the implementation of *f*.
R is the *postcondition* of *f*.

- $\{true\}$ S $\{R\}$
  All input values are valid [Most-user friendly]
- $\{false\}$ S $\{R\}$
  All input values are invalid [Most useless for clients]
- $\{Q\}$ S $\{true\}$
  All output values are valid [Most risky for clients; Easiest for suppliers]
- $\{Q\}$ S $\{false\}$
  All output values are invalid [Most challenging coding task]
- $\{true\}$ S $\{true\}$
  All inputs/outputs are valid (No contracts) [Least informative]

Proof of Hoare Triple using *wp*

$$\{Q\}\ S\ \{R\} \equiv Q \Rightarrow wp(S, R)$$

- $wp(S, R)$ is the *weakest precondition for S to establish R*.
- *S* can be:
  - Assignments (`x := y`)
  - Alternations (**if** ... **then** ... **else** ... **end**)
  - Sequential compositions (S_1 ; S_2)
  - Loops (**from** ... **until** ... **loop** ... **end**)
- We will learn how to calculate the *wp* for the above programming constructs.

Hoare Logic A Simple Example

Given $\{??\} n := n + 9 \{n > 13\}$:

- $\boxed{n > 4}$ is the *weakest precondition (wp)* for the given implementation (n := n + 9) to start and establish the postcondition ($n > 13$).
- Any precondition that is ***equal to or stronger than*** the *wp* ($n > 4$) will result in a correct program.

  e.g., $\{n > 5\} n := n + 9 \{n > 13\}$ can be proved **TRUE**.
- Any precondition that is ***weaker than*** the *wp* ($n > 4$) will result in an incorrect program.

  e.g., $\{n > 3\} n := n + 9 \{n > 13\}$ cannot be proved **TRUE**.

  Counterexample: $n = 4$ satisfies precondition $n > 3$ but the output $n = 13$ fails postcondition $n > 13$.

Denoting New and Old Values

In the *postcondition*, for a program variable x:

- We write $\boxed{x_0}$ to denote its ***pre-state (old)*** value.
- We write $\boxed{x}$ to denote its ***post-state (new)*** value.

  Implicitly, in the *precondition*, all program variables have their ***pre-state*** values.

e.g., $\{b_0 > a\}$ `b := b - a` $\{b = b_0 - a\}$

- Notice that:
  - We may choose to write "b" rather than "b_0" in preconditions

    $\because$ All variables are pre-state values in preconditions
  - We don't write "b_0" in program

    $\because$ there might be *multiple intermediate values* of a variable due to sequential composition

wp Rule: Assignments (1)

$$wp(\texttt{x := e}, R) = R[x := e]$$

$R[x := e]$ means to substitute all *free occurrences* of variable x in postcondition R by expression e.

wp Rule: Assignments (2)

Recall:

$$\{Q\}\ \texttt{S}\ \{R\} \equiv Q \Rightarrow wp(S, R)$$

How do we prove $\{Q\}$ `x := e` $\{R\}$?

$$\{Q\}\ \texttt{x := e}\ \{R\} \iff Q \Rightarrow \underbrace{R[x := e]}_{wp(\texttt{x := e}, R)}$$

wp Rule: Assignments (3) Exercise

What is the weakest precondition for a program `x := x + 1` to establish the postcondition $x > x_0$?

$$\{??\}\ \texttt{x := x + 1}\ \{x > x_0\}$$

For the above Hoare triple to be ***TRUE***, it must be that $?? \Rightarrow wp(\texttt{x := x + 1}, x > x_0)$.

$$
\begin{array}{ll}
 & wp(\texttt{x := x + 1}, x > x_0) \\
= & \{\textit{Rule of wp: Assignments}\} \\
 & x > x_0[x := x_0 + 1] \\
= & \{\textit{Replacing } x \textit{ by } x_0 + 1\} \\
 & x_0 + 1 > x_0 \\
= & \{1 > 0 \textit{ always true}\} \\
 & \textit{True}
\end{array}
$$

Any precondition is OK. ***False*** is valid but not useful.

wp Rule: Assignments (4) Exercise

What is the weakest precondition for a program `x := x + 1` to establish the postcondition $x > x_0$?

$$\{??\}\ \texttt{x := x + 1}\ \{x = 23\}$$

For the above Hoare triple to be ***TRUE***, it must be that $?? \Rightarrow wp(\texttt{x := x + 1}, x = 23)$.

$$
\begin{array}{ll}
 & wp(\texttt{x := x + 1}, x = 23) \\
= & \{\textit{Rule of wp: Assignments}\} \\
 & x = 23[x := x_0 + 1] \\
= & \{\textit{Replacing } x \textit{ by } x_0 + 1\} \\
 & x_0 + 1 = 23 \\
= & \{\textit{arithmetic}\} \\
 & x_0 = 22
\end{array}
$$

Any precondition weaker than $x = 22$ is not OK.

wp Rule: Alternations (1)

$$wp(\texttt{if } B \texttt{ then } S_1 \texttt{ else } S_2 \texttt{ end}, R) = \left(\begin{array}{l} B \Rightarrow wp(S_1, R) \\ \land \\ \neg B \Rightarrow wp(S_2, R) \end{array}\right)$$

The *wp* of an alternation is such that ***all branches*** are able to establish the postcondition ***R***.

wp Rule: Alternations (2)

Recall: $\{Q\}\ S\ \{R\} \equiv Q \Rightarrow wp(S, R)$

How do we prove that $\{Q\}$ `if` B `then` S_1 `else` S_2 `end` $\{R\}$?

```
{Q}
if B then
  {Q ∧ B} S1 {R}
else
  {Q ∧ ¬B} S2 {R}
end
{R}
```

$$\{Q\}\ \texttt{if } B \texttt{ then } S_1 \texttt{ else } S_2 \texttt{ end}\ \{R\}$$

$$\iff \left(\begin{array}{l} \{\ Q \land B\ \}\ S_1\ \{\ R\ \} \\ \land \\ \{\ Q \land \neg B\ \}\ S_2\ \{\ R\ \} \end{array}\right) \iff \left(\begin{array}{l} (Q \land B) \Rightarrow wp(S_1, R) \\ \land \\ (Q \land \neg B) \Rightarrow wp(S_2, R) \end{array}\right)$$

wp Rule: Alternations (3) Exercise

Is this program correct?

```
{x > 0 ∧ y > 0}
if x > y then
  bigger := x ; smaller := y
else
  bigger := y ; smaller := x
end
{bigger ≥ smaller}
```

$$\left(\begin{array}{l}\{(x>0 \land y>0) \land (x>y)\} \\ \quad \texttt{bigger := x ; smaller := y} \\ \{bigger \geq smaller\}\end{array}\right) \land \left(\begin{array}{l}\{(x>0 \land y>0) \land \neg(x>y)\} \\ \quad \texttt{bigger := y ; smaller := x} \\ \{bigger \geq smaller\}\end{array}\right)$$

wp Rule: Sequential Composition (1)

$$wp(S_1\ ;\ S_2, R) = wp(S_1, wp(S_2, R))$$

The *wp* of a sequential composition is such that the first phase establishes the *wp* for the second phase to establish the postcondition ***R***.

wp Rule: Sequential Composition (2)

Recall:

$$\{Q\}\ \texttt{S}\ \{R\} \equiv Q \Rightarrow wp(S, R)$$

How do we prove $\{Q\}\ S_1\ ;\ S_2\ \{R\}$?

$$\{Q\}\ S_1\ ;\ S_2\ \{R\} \iff Q \Rightarrow \underbrace{wp(S_1, wp(S_2, R))}_{wp(S_1\ ;\ S_2, R)}$$

wp Rule: Sequential Composition (3) Exercise

Is $\{\ True\ \}$ `tmp := x; x := y; y := tmp` $\{\ x > y\ \}$ correct?
If and only if $True \Rightarrow wp(\texttt{tmp := x ; x := y ; y := tmp}, x > y)$

$$\begin{array}{ll}
 & wp(\texttt{tmp := x ; }\boxed{\texttt{x := y ; y := tmp}}, x > y) \\
= & \{wp \textit{ rule for seq. comp.}\} \\
 & wp(\texttt{tmp := x}, wp(\texttt{x := y ; }\boxed{\texttt{y := tmp}}, x > y)) \\
= & \{wp \textit{ rule for seq. comp.}\} \\
 & wp(\texttt{tmp := x}, wp(\texttt{x := y}, wp(\texttt{y := tmp}, x > \boxed{y}))) \\
= & \{wp \textit{ rule for assignment}\} \\
 & wp(\texttt{tmp := x}, wp(\texttt{x := y}, \boxed{x} > tmp)) \\
= & \{wp \textit{ rule for assignment}\} \\
 & wp(\texttt{tmp := x}, y > \boxed{tmp}) \\
= & \{wp \textit{ rule for assignment}\} \\
 & y > x
\end{array}$$

$\because$ $True \Rightarrow y > x$ does not hold in general.
$\therefore$ The above program is not correct.

Loops

- A loop is a way to compute a certain result by *successive approximations*.

  e.g. computing the maximum value of an array of integers
- Loops are needed and powerful
- But loops *very hard* to get right:
  - Infinite loops [termination]
  - "off-by-one" error [partial correctness]
  - Improper handling of borderline cases [partial correctness]
  - Not establishing the desired condition [partial correctness]

Loops: Binary Search

BS1

```
from
    i := 1; j := n
until i = j loop
    m := (i + j) // 2
    if t @ m <= x then
        i := m
    else
        j := m
    end
end
Result := (x = t @ i)
```

BS2

```
from
    i := 1; j := n; found := false
until i = j and not found loop
    m := (i + j) // 2
    if t @ m < x then
        i := m + 1
    elseif t @ m = x then
        found := true
    else
        j := m – 1
    end
end
Result := found
```

BS3

```
from
i := 0; j := n
until i = j loop
    m := (i + j + 1) // 2
    if t @ m <= x then
        i := m + 1
    else
        j := m
    end
end
if i >= 1 and i <= n then
    Result := (x = t @ i)
else
    Result := false
end
```

BS4

```
from
    i := 0; j := n + 1
until i = j loop
    m := (i + j) // 2
    if t @ m <= x then
        i := m + 1
    else
        j := m
    end
end
if i >= 1 and i <= n then
    Result := (x = t @ i)
else
    Result := false
end
```

4 implementations for binary search: published, but *wrong*!

See page 381 in *Object Oriented Software Construction*

Correctness of Loops

How do we prove that the following loops are correct?

```
{Q}
from
  S_init
until
  B
loop
  S_body
end
{R}
```

```
{Q}
S_init
while(¬ B) {
  S_body
}
{R}
```

- In case of C/Java, $\neg B$ denotes the ***stay condition***.
- In case of Eiffel, B denotes the ***exit condition***.

  There is native, syntactic support for checking/proving the *total correctness* of loops.

Contracts for Loops: Syntax

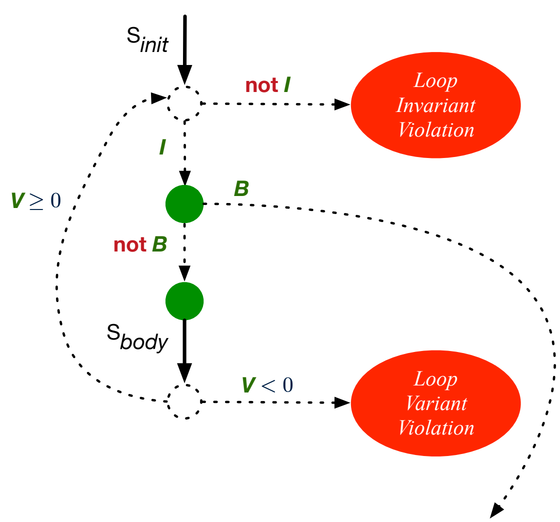
```
from
  S_init
invariant
  invariant_tag: I -- Boolean expression for partial correctness
until
  B
loop
  S_body
variant
  variant_tag: V -- Integer expression for termination
end
```

Contracts for Loops

- Use of ***loop invariants (LI)*** and ***loop variants (LV)***.
  - ***Invariants***: Boolean expressions for ***partial*** *correctness*.
    - Typically a special case of the postcondition.
      e.g., Given postcondition “ *Result is maximum of the array* ”:
      LI can be “ *Result is maximum of the* ***part of array scanned so far*** ”.
    - Established before the very first iteration.
    - Maintained TRUE after each iteration.
  - ***Variants***: Integer expressions for ***termination***
    - Denotes the *number of iterations remaining*
    - *Decreased* at the end of each subsequent iteration
    - Maintained *non-negative* at the end of each iteration.
    - As soon as value of ***LV*** reaches *zero*, meaning that no more iterations remaining, the loop must exit.
- Remember:

  total *correctness* = ***partial*** *correctness* + ***termination***

Contracts for Loops: Runtime Checks (1)



Contracts for Loops: Runtime Checks (2)

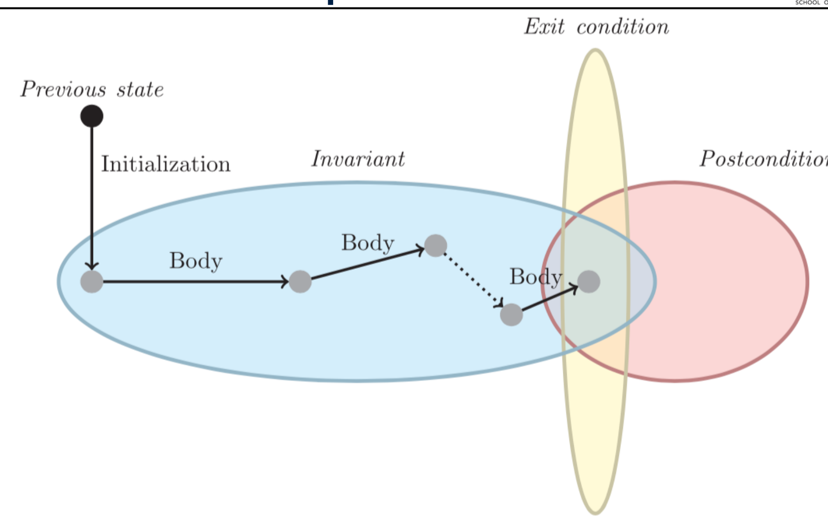
```
1  test
2    local
3      i: INTEGER
4    do
5      from
6        i := 1
7      invariant
8        1 <= i and i <= 6
9      until
10       i > 5
11     loop
12       io.put_string ("iteration " + i.out + "%N")
13       i := i + 1
14     variant
15       6 - i
16     end
17 end
```

L8: Change to `1 <= i and i <= 5` for a ***Loop Invariant Violation***.

L10: Change to `i > 0` to bypass the body of loop.

L15: Change to `5 - i` for a ***Loop Variant Violation***.

Contracts for Loops: Visualization



Digram Source: page 5 in *Loop Invariants: Analysis, Classification, and Examples*

Contracts for Loops: Example 1.1

```
find_max (a: ARRAY [INTEGER]): INTEGER
  local i: INTEGER
  do
    from
      i := a.lower ; Result := a[i]
    invariant
      loop_invariant: -- ∀j | a.lower ≤ j ≤ i • Result ≥ a[j]
        across a.lower |..| i as j all Result >= a [j.item] end
    until
      i > a.upper
    loop
      if a [i] > Result then Result := a [i] end
      i := i + 1
    variant
      loop_variant: a.upper - i + 1
    end
  ensure
    correct_result: -- ∀j | a.lower ≤ j ≤ a.upper • Result ≥ a[j]
      across a.lower |..| a.upper as j all Result >= a [j.item]
  end
end
```


Contracts for Loops: Example 1.2

Consider the feature call find_max(⟨⟨20, 10, 40, 30⟩⟩), given:

- ***Loop Invariant***: $\forall j \mid a.lower \le j \le i \bullet Result \ge a[j]$
- ***Loop Variant***: $a.upper - i + 1$

AFTER ITERATION	i	Result	*LI*	EXIT ($i > a.upper$)?	*LV*
Initialization	1	20	✓	×	–
1st	2	20	✓	×	3
2nd	***3***	20	×	–	–

Loop invariant violation at the end of the 2nd iteration:

$$\forall j \mid a.lower \le j \le \boxed{3} \bullet \boxed{20} \ge a[j]$$

evaluates to ***false*** $\because 20 \not\ge a[3] = 40$

Contracts for Loops: Example 2.1

```
find_max (a: ARRAY [INTEGER]): INTEGER
  local i: INTEGER
  do
    from
      i := a.lower ; Result := a[i]
    invariant
      loop_invariant: -- ∀j | a.lower ≤ j < i • Result ≥ a[j]
        across a.lower |..| (i - 1) as j all Result >= a [j.item] end
    until
      i > a.upper
    loop
      if a [i] > Result then Result := a [i] end
      i := i + 1
    variant
      loop_variant: a.upper - i
    end
  ensure
    correct_result: -- ∀j | a.lower ≤ j ≤ a.upper • Result ≥ a[j]
      across a.lower |..| a.upper as j all Result >= a [j.item]
  end
end
```


Contracts for Loops: Example 2.2

Consider the feature call find_max(⟨⟨20, 10, 40, 30⟩⟩), given:

- ***Loop Invariant***: $\forall j \mid a.lower \le j < i \bullet Result \ge a[j]$
- ***Loop Variant***: $a.upper - i$

AFTER ITERATION	i	Result	*LI*	EXIT ($i > a.upper$)?	*LV*
Initialization	1	20	✓	×	–
1st	2	20	✓	×	2
2nd	3	20	✓	×	1
3rd	4	40	✓	×	0
4th	5	40	✓	✓	***-1***

Loop variant violation at the end of the 2nd iteration
$\because a.upper - i = 4 - 5$ evaluates to ***non-zero***.

Contracts for Loops: Example 3.1

```
find_max (a: ARRAY [INTEGER]): INTEGER
  local i: INTEGER
  do
    from
      i := a.lower ; Result := a[i]
    invariant
      loop_invariant: -- ∀j | a.lower ≤ j < i • Result ≥ a[j]
        across a.lower |..| (i - 1) as j all Result >= a [j.item] end
    until
      i > a.upper
    loop
      if a [i] > Result then Result := a [i] end
      i := i + 1
    variant
      loop_variant: a.upper - i + 1
    end
  ensure
    correct_result: -- ∀j | a.lower ≤ j ≤ a.upper • Result ≥ a[j]
      across a.lower |..| a.upper as j all Result >= a [j.item]
  end
end
```


Contracts for Loops: Example 3.2

Consider the feature call find_max(⟨⟨20, 10, 40, 30⟩⟩), given:

- ***Loop Invariant***: $\forall j \mid a.lower \le j < i \bullet Result \ge a[j]$
- ***Loop Variant***: $a.upper - i + 1$
- *Postcondition*: $\forall j \mid a.lower \le j \le a.upper \bullet Result \ge a[j]$

AFTER ITERATION	i	Result	*LI*	EXIT ($i > a.upper$)?	*LV*
Initialization	1	20	✓	×	–
1st	2	20	✓	×	3
2nd	3	20	✓	×	2
3rd	4	40	✓	×	1
4th	5	40	✓	✓	0

Contracts for Loops: Exercise

```
class DICTIONARY[V, K]
feature {NONE} -- Implementations
  values: ARRAY[K]
  keys: ARRAY[K]
feature -- Abstraction Function
  model: FUN[K, V]
feature -- Queries
  get_keys(v: V): ITERABLE[K]
    local i: INTEGER; ks: LINKED_LIST[K]
    do
      from i := keys.lower ; create ks.make_empty
      invariant ??
      until i > keys.upper
      do if values[i] ~ v then ks.extend(keys[i]) end
      end
      Result := ks.new_cursor
    ensure
      result_valid: ∀k | k ∈ Result • model.item(k) ~ v
      no_missing_keys: ∀k | k ∈ model.domain • model.item(k) ~ v ⇒ k ∈ Result
    end
```


Proving Correctness of Loops (1)

```
{Q}   from
        S_init
      invariant
        I
      until
        B
      loop
        S_body
      variant
        V
      end    {R}
```

- A loop is ***partially correct*** if:
  - Given precondition ***Q***, the initialization step S_{init} establishes ***LI*** I.
  - At the end of S_{body}, if not yet to exit, ***LI*** I is maintained.
  - If ready to exit and ***LI*** I maintained, postcondition ***R*** is established.
- A loop *terminates* if:
  - Given ***LI*** I, and not yet to exit, S_{body} maintains ***LV*** V as non-negative.
  - Given ***LI*** I, and not yet to exit, S_{body} decrements ***LV*** V.

Proving Correctness of Loops (2)

$\{Q\}$ **from** S_{init} **invariant** I **until** B **loop** S_{body} **variant** V **end** $\{R\}$

- A loop is ***partially correct*** if:
  - Given precondition Q, the initialization step S_{init} establishes ***LI*** I.
    $$\{Q\}\ S_{init}\ \{I\}$$
  - At the end of S_{body}, if not yet to exit, ***LI*** I is maintained.
    $$\{I \wedge \neg B\}\ S_{body}\ \{I\}$$
  - If ready to exit and ***LI*** I maintained, postcondition R is established.
    $$I \wedge B \Rightarrow R$$
- A loop *terminates* if:
  - Given ***LI*** I, and not yet to exit, S_{body} maintains ***LV*** V as non-negative.
    $$\{I \wedge \neg B\}\ S_{body}\ \{V \geq 0\}$$
  - Given ***LI*** I, and not yet to exit, S_{body} decrements ***LV*** V.
    $$\{I \wedge \neg B\}\ S_{body}\ \{V < V_0\}$$

Proving Correctness of Loops: Exercise (1.1)

Prove that the following program is correct:

```
find_max (a: ARRAY [INTEGER]): INTEGER
  local i: INTEGER
  do
    from
      i := a.lower ; Result := a[i]
    invariant
      loop_invariant: ∀j | a.lower ≤ j < i • Result ≥ a[j]
    until
      i > a.upper
    loop
      if a [i] > Result then Result := a [i] end
      i := i + 1
    variant
      loop_variant: a.upper − i + 1
    end
  ensure
    correct_result: ∀j | a.lower ≤ j ≤ a.upper • Result ≥ a[j]
  end
end
```


Proving Correctness of Loops: Exercise (1.2)

Prove that each of the following *Hoare Triples* is TRUE.

1. **Establishment of Loop Invariant:**

```
{ True }
  i := a.lower
  Result := a[i]
{ ∀j | a.lower ≤ j < i • Result ≥ a[j] }
```

2. **Maintenance of Loop Invariant:**

```
{ (∀j | a.lower ≤ j < i • Result ≥ a[j]) ∧ ¬(i > a.upper) }
  if a [i] > Result then Result := a [i] end
  i := i + 1
{ (∀j | a.lower ≤ j < i • Result ≥ a[j]) }
```

3. **Establishment of Postcondition upon Termination:**

$$(\forall j \mid a.lower \leq j < i \bullet Result \geq a[j]) \wedge i > a.upper$$
$$\Rightarrow \forall j \mid a.lower \leq j \leq a.upper \bullet Result \geq a[j]$$

Proving Correctness of Loops: Exercise (1.3)

Prove that each of the following *Hoare Triples* is TRUE.

4. **Loop Variant Stays Non-Negative Before Exit:**

```
{ (∀j | a.lower ≤ j < i • Result ≥ a[j]) ∧ ¬(i > a.upper) }
  if a [i] > Result then Result := a [i] end
  i := i + 1
{ a.upper − i + 1 ≥ 0 }
```

5. **Loop Variant Keeps Decrementing before Exit:**

```
{ (∀j | a.lower ≤ j < i • Result ≥ a[j]) ∧ ¬(i > a.upper) }
  if a [i] > Result then Result := a [i] end
  i := i + 1
{ a.upper − i + 1 < (a.upper − i + 1)₀ }
```

where $(a.upper - i + 1)_0 \equiv a.upper_0 - i_0 + 1$

Proof Tips (1)

$$\{Q\}\ \text{S}\ \{R\} \Rightarrow \{Q \wedge P\}\ \text{S}\ \{R\}$$

In order to prove $\{Q \wedge P\}\ \text{S}\ \{R\}$, it is sufficient to prove a version with a *weaker* precondition: $\{Q\}\ \text{S}\ \{R\}$.

Proof:

- Assume: $\{Q\}\ \text{S}\ \{R\}$
  It's equivalent to assuming: $\boxed{Q} \Rightarrow wp(\text{S}, R)$ **(A1)**
- To prove: $\{Q \wedge P\}\ \text{S}\ \{R\}$
  - It's equivalent to proving: $Q \wedge P \Rightarrow wp(\text{S}, R)$
  - Assume: $Q \wedge P$, which implies $\boxed{Q}$
  - According to **(A1)**, we have $wp(\text{S}, R)$. ■

Proof Tips (2)

When calculating $wp(\text{S}, R)$, if either program S or postcondition R involves array indexing, then R should be augmented accordingly.

e.g., Before calculating $wp(\text{S}, a[i] > 0)$, augment it as

$$wp(\text{S}, a.lower \leq i \leq a.upper \wedge a[i] > 0)$$

e.g., Before calculating $wp(\texttt{x := a[i]}, R)$, augment it as

$$wp(\texttt{x := a[i]}, a.lower \leq i \leq a.upper \wedge R)$$

Index (1)

Index (2)

Index (3)