Design-by-Contract (DbC)

Readings: OOSC2 Chapters 6, 7, 8, 11

EECS3311 A & E: Software Design
Fall 2020

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Learning Objectives

Upon completing this lecture, you are expected to understand:

1. *Design by Contract* (*DbC*): Motivation & Terminology
2. Supporting *DbC* (Java vs. Eiffel): *Preconditions*, *Postconditions*, *Class Invariants*
3. *Runtime Assertion Checking* of Contracts

Part 1

Design by Contract (DbC): Motivation & Terminology

Motivation: Catching Defects – When?

- To minimize *development costs*, minimize *software defects*.
- Software Development Cycle:
  Requirements → *Design* → *Implementation* → Release
  Q. Design or Implementation Phase?
  Catch defects *as early as possible*.

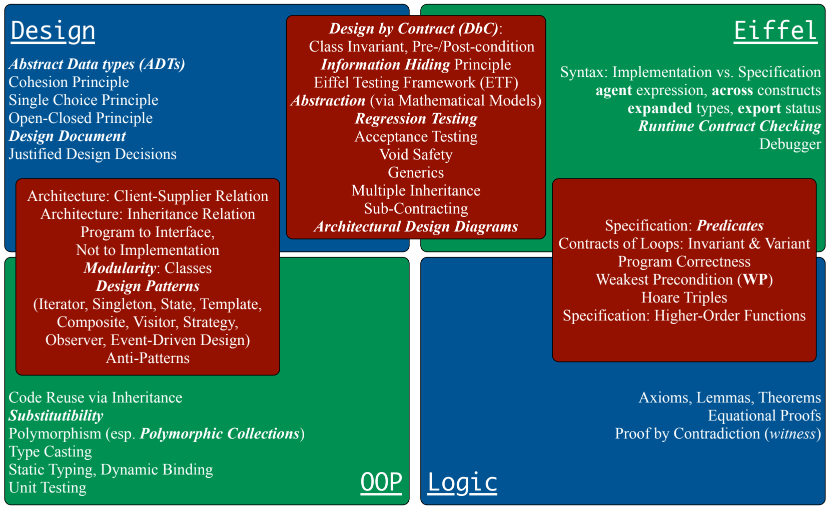
Design and architecture	Implementation	Integration testing	Customer beta test	Postproduct release
1X*	5X	10X	15X	30X

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

- 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: IBM Report

What this Course Is About (1)



What this Course Is About (2)

- 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 is 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 call 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)*.

Part 2.1

Supporting DbC in Java:
Problem & 1st Attempt (No Contracts)

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 Java project archive (a zip file) here:

  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/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

V1: An Account Class

```
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.

V1: Why Not a Good Design? (1)

```
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

V1: Why Not a Good Design? (2)

```
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`.

V1: Why Not a Good Design? (3)

```
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`.

V1: 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]

Part 2.2

Supporting DbC in Java:
2^{nd} Attempt (Method Preconditions)

V1: 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 V2 by adding *exceptional conditions* (an *approximation* of *preconditions*) to the constructor and `withdraw` method of the `Account` class.

V2: Preconditions ≈ Exceptions

```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; }
  }
```


V2: Why Better than V1? (1)

```java
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*.

V2: Why Better than V1? (2.1)

```java
1  public class BankAppV2 {
2   public static void main(String[] args) {
3    System.out.println("Create an account for Mark with balance 100:");
4    try {
5     AccountV2 mark = new AccountV2("Mark", 100);
6     System.out.println(mark);
7     System.out.println("Withdraw -1000000 from Mark's account:");
8     mark. withdraw(-1000000) ;
9     System.out.println(mark);
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   }
```


V2: Why Better than V1? (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.
```

- **L8**: 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 *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!!

V2: Why Better than V1? (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   }
```


V2: Why Better than V1? (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.
```

- **L8**: 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 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!!

V2: Why Still Not a Good Design? (1)

```
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; }
 }
```

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

V2: Why Still Not a Good Design? (2.1)

```
public class BankAppV2 {
 public static void main(String[] args) {
  System.out.println("Create an account for Jim with balance 100:");
  try {
   AccountV2 jim = new AccountV2("Jim", 100);
   System.out.println(jim);
   System.out.println("Withdraw 100 from Jim's account:");
   jim. withdraw(100) ;
   System.out.println(jim);
  }
  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.");
  }
```

V2: 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`.

Part 2.3

Supporting DbC in Java:
3rd Attempt (Class Invariants)

V2: 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 **V3** by adding *assertions* to the end of constructor and `withdraw` method of the `Account` class.

V3: Class Invariants ≈ Assertions

```java
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";
  }
```

V3: Why Better than V2?

```
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          * V2: 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*.

V3: Why Still Not a Good Design?

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

- From V2 : *exceptions* encoding **negated** *preconditions*
- From V3 : *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 V4 , where deliberately mistakenly implement `withdraw`.

Part 2.4

Supporting DbC in Java:
4^{th} Attempt (Faulty Implementation)

V4: `withdraw` implemented incorrectly? (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* .

V4: `withdraw` implemented incorrectly? (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    * V2: 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**

Part 2.5

Supporting DbC in Java:
5th Attempt (Method Postconditions)

V4: 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)`?
    $[\,\textbf{Result} \times y == x\,]$
  - Postcondition of `boolean binSearch(int x, int[] xs)`?
    $[\,x \in xs \iff \textbf{Result}\,]$
- 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 V5 by adding *assertions* to the end of `withdraw` method of the `Account` class.

V5: Postconditions ≈ Assertions

```
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**.

V5: Why Better than V4?

```
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            * V2: 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*.

Part 2.6

Supporting DbC: Java vs. Eiffel

Evolving from V1 to V5

	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*	–
V4	Deliberately changed `withdraw`'s implementation to be **incorrect**.	Incorrect implementations do not necessarily 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.

V5: 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: 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: 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: 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 Command

```
some_command (x: SOME_TYPE_1; y: SOME_TYPE_2)
   -- 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***

DbC in Eiffel: Anatomy of a Query

```
some_query (x: SOME_TYPE_1; y: SOME_TYPE_2): SOME_RT
   -- Description of the query.
 require
   -- List of tagged boolean expressions for preconditions
 local
   -- List of local variable declarations
 do
   -- List of instructions as implementation
   Result := ...
 ensure
   -- List of tagged boolean expressions for postconditions
 end
```

- Each query has a predefined variable **`Result`**.
- Implicitly, you may think of:
  - First line of the query declares **`Result`**: *`SOME_RT`*
  - Last line of the query return the value of **`Result`**.

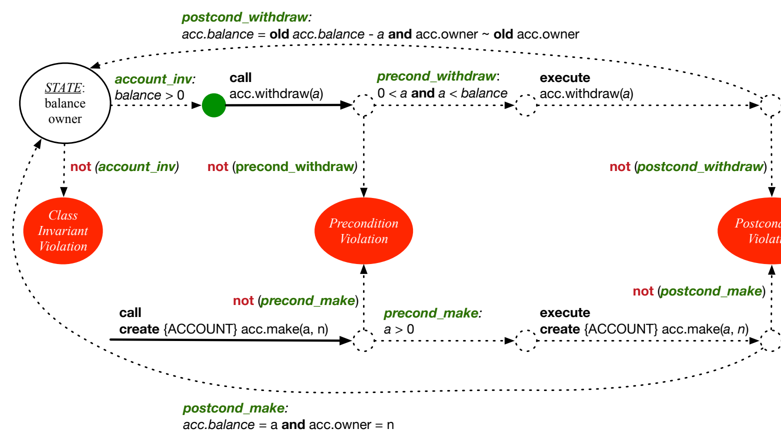
    ⇒ Manipulate **`Result`** so that its last value is the desired result.

Part 3

DbC in Eiffel: Runtime Checking

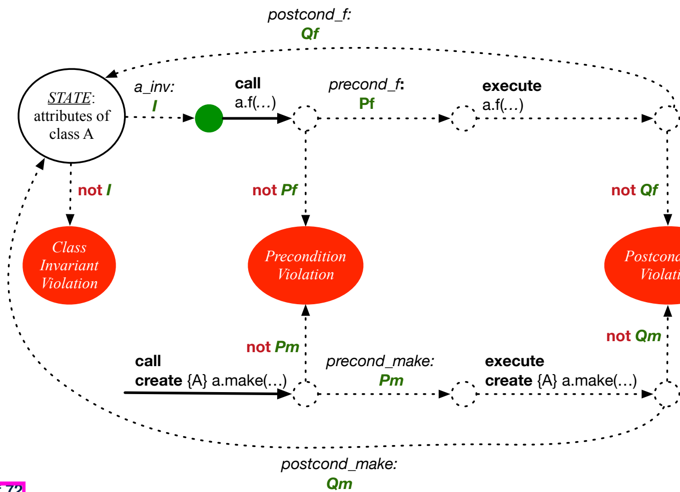
Runtime Monitoring of Contracts (1)

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.

Experimenting Contract Violations in Eiffel

- **Download** the Eiffel project archive (a zip file) here:

  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/codes/DbCIntroEiffel.zip
- Unzip and compile the project in Eiffel Studio.
- Follow the in-code comments to re-produce the various ***contract violations*** and understand from the ***stack trace*** how they occur.

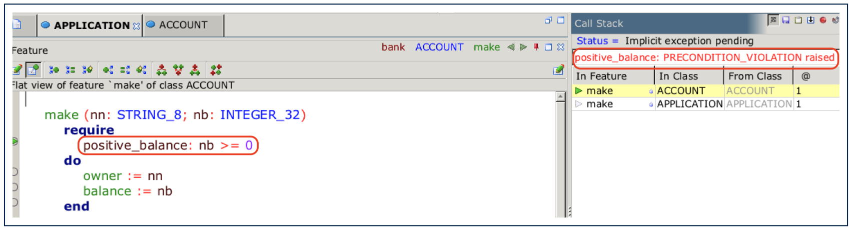
DbC in Eiffel: Precondition Violation (1.1)

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)



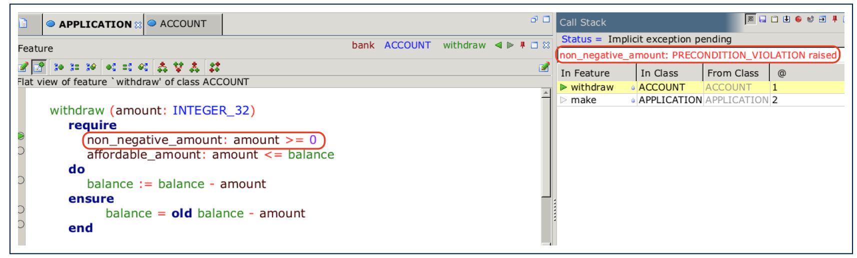
DbC in Eiffel: Precondition Violation (2.1)

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)



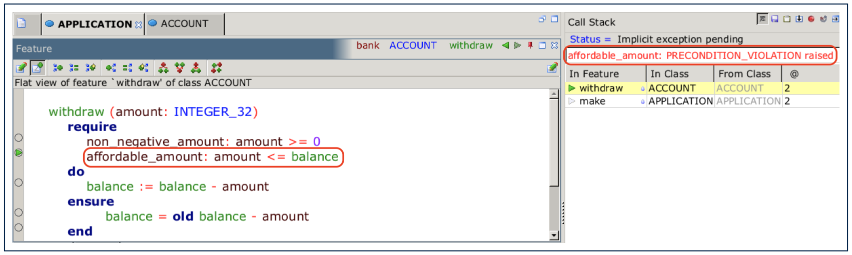
DbC in Eiffel: Precondition Violation (3.1)

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)



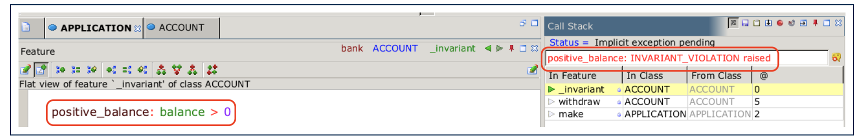
DbC in Eiffel: Class Invariant Violation (4.1)

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)



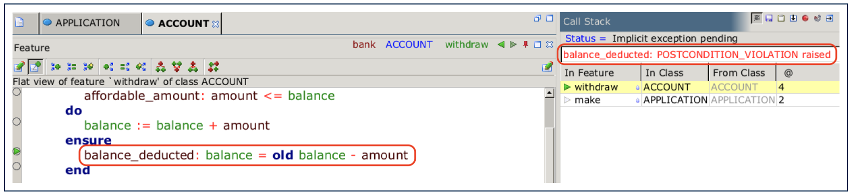
DbC in Eiffel: Postcondition Violation (5.1)

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)



Beyond this lecture...

1. Review your Lab0 tutorial about how DbC is supported in Eiffel.
2. Explore in Eclipse how *contract* checks are *manually-coded*:
   `https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/codes/DbCIntro.zip`
3. Recall the 4th requirement of the bank problem (see here):

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

   Design the header of this `add` method, implement it, and encode proper pre-condition and ***post-condition*** for it.
   Q. What postcondition can you think of? Does it require any skill from EECS1090? What attribute value(s) do you need to manually store in the ***pre-state***?
4. 3 short courses which will help your labs and project:
   - Eiffel Syntax: here.
   - Common Syntax/Type Errors in Eiffel: here.
   - Drawing Design Diagrams: here.

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Modularity
Abstract Data Types (ADTs)

YORK UNIVERSITÉ UNIVERSITY

EECS3311 A & E: Software Design
Fall 2020

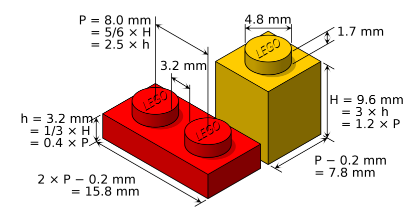
CHEN-WEI WANG

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Criterion of *Modularity*, Modular Design
2. *Abstract Data Types* (*ADTs*)

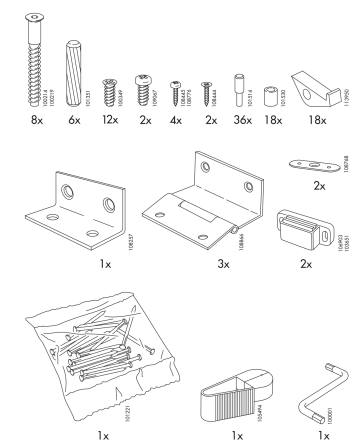
Modularity (1): Childhood Activity

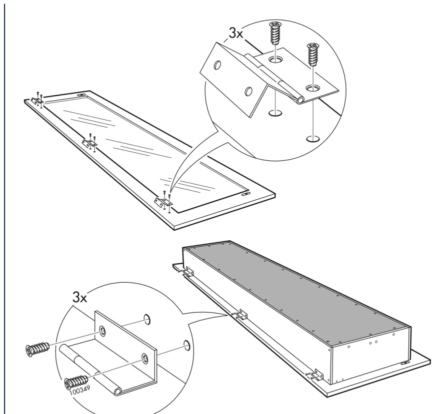


(INTERFACE) SPECIFICATION | (ASSEMBLY) ARCHITECTURE

Sources: `https://commons.wikimedia.org` and `https://www.wish.com`

Modularity (2): Daily Construction



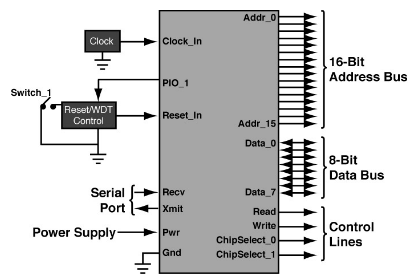


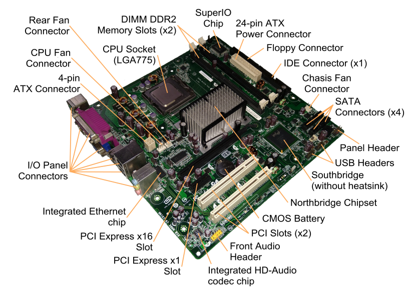
(INTERFACE) SPECIFICATION | (ASSEMBLY) ARCHITECTURE

Source: `https://usermanual.wiki/`

Modularity (3): Computer Architecture

Motherboards are built from functioning units (e.g., *CPUs*).





(INTERFACE) SPECIFICATION || (ASSEMBLY) ARCHITECTURE

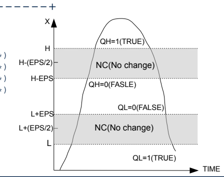
Sources: www.embeddedlinux.org.cn and https://en.wikipedia.org

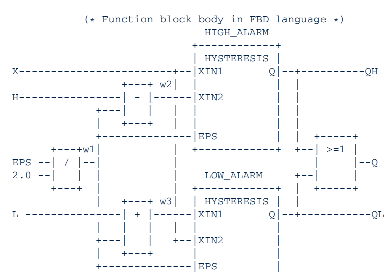
Modularity (4): System Development

Safety-critical systems (e.g., *nuclear shutdown systems*) are built from *function blocks*.

```
(* DECLARATION *)
       +----------+
       | LIMITS_  |
       | ALARM    |
REAL--|H       QH|--BOOL
REAL--|X        Q|--BOOL
REAL--|L       QL|--BOOL
REAL--|EPS       |
       +----------+
```

```
FUNCTION_BLOCK LIMITS_ALARM
  VAR_INPUT
    H   : REAL; (* High limit     *)
    X   : REAL; (* Variable value *)
    L   : REAL; (* Lower limit    *)
    EPS : REAL; (* Hysteresis     *)
  END_VAR
  VAR_OUTPUT
    QH : BOOL; (* High flag    *)
    Q  : BOOL; (* Alarm output *)
    QL : BOOL; (* Low flag     *)
  END_VAR
END_FUNCTION_BLOCK
```



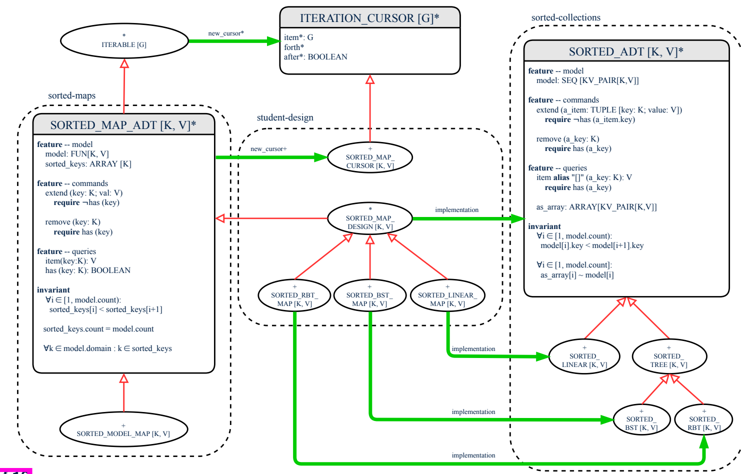


(INTERFACE) SPECIFICATION || (ASSEMBLY) ARCHITECTURE

Sources: https://plcopen.org/iec-61131-3

Modularity (5): Software Design

Software systems are composed of well-specified *classes*.

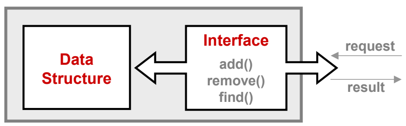


Design Principle: Modularity

- *Modularity* refers to a sound quality of your design:
  1. **Divide** a given complex ***problem*** into inter-related ***sub-problems*** via a logical/justifiable functional decomposition.
     e.g., In designing a game, solve sub-problems of: 1) rules of the game; 2) actor characterizations; and 3) presentation.
  2. **Specify** each ***sub-solution*** as a *module* with a clear **interface**: inputs, outputs, and **input-output relations**.
     - The UNIX principle: Each command does one thing and does it well.
     - In objected-oriented design (OOD), each class serves as a module.
  3. **Conquer** original ***problem*** by assembling ***sub-solutions***.
     - In OOD, classes are assembled via client-supplier relations (aggregations or compositions) or inheritance relations.
- A *modular design* satisfies the criterion of modularity and is:
  - ***Maintainable***: fix issues by changing the relevant modules only.
  - ***Extensible***: introduce new functionalities by adding new modules.
  - ***Reusable***: a module may be used in different compositions
- Opposite of modularity: A *superman module* doing everything.

Abstract Data Types (ADTs)

- Given a problem, decompose its solution into *modules*.
- Each *module* implements an *abstract data type (ADT)*:
  - filters out *irrelevant* details
  - contains a list of declared data and *well-specified* operations



- Supplier's Obligations:
  - Implement all operations
  - Choose the "right" data structure (DS)
- Client's Benefits:
  - Correct output
  - Efficient performance
- The internal details of an *implemented ADT* should be **hidden**.

Building ADTs for Reusability

- ADTs are *reusable software components*
  e.g., Stacks, Queues, Lists, Dictionaries, Trees, Graphs
- An ADT, once thoroughly tested, can be reused by:
  - Suppliers of other ADTs
  - Clients of Applications
- As a supplier, you are obliged to:
  - *Implement* given ADTs using other ADTs (e.g., arrays, linked lists, hash tables, etc.)
  - *Design* algorithms that make use of standard ADTs
- For each ADT that you build, you ought to be clear about:
  - The list of supported operations (i.e., *interface*)
    - The interface of an ADT should be *more than* method signatures and natural language descriptions:
    - How are clients supposed to use these methods? [*preconditions*]
    - What are the services provided by suppliers? [*postconditions*]
  - Time (and sometimes space) *complexity* of each operation

Why Java Interfaces Unacceptable ADTs (1)

Interface List<E>

Type Parameters:
E - the type of elements in this list

All Superinterfaces:
Collection<E>, Iterable<E>

All Known Implementing Classes:
AbstractList, AbstractSequentialList, ArrayList, AttributeList, CopyOnWriteArrayList, LinkedList, RoleList, RoleUnresolvedList, Stack, Vector

```
public interface List<E>
extends Collection<E>
```

An ordered collection (also known as a *sequence*). The user of this interface has precise control over where in the list each element is inserted. The user can access elements by their integer index (position in the list), and search for elements in the list.

It is useful to have:

- A *generic collection class* where the ***homogeneous type*** of elements are parameterized as `E`.
- A reasonably ***intuitive overview*** of the ADT.

Java 8 List API

Why Java Interfaces Unacceptable ADTs (2)

Methods described in a ***natural language*** can be ***ambiguous***:

E	set(int index, E element) Replaces the element at the specified position in this list with the specified element (optional operation).

set

```
E set(int index,
      E element)
```

Replaces the element at the specified position in this list with the specified element (optional operation).

Parameters:
index - index of the element to replace
element - element to be stored at the specified position

Returns:
the element previously at the specified position

Throws:
UnsupportedOperationException - if the set operation is not supported by this list
ClassCastException - if the class of the specified element prevents it from being added to this list
NullPointerException - if the specified element is null and this list does not permit null elements
IllegalArgumentException - if some property of the specified element prevents it from being added to this list
IndexOutOfBoundsException - if the index is out of range (index < 0 || index >= size())

Why Eiffel Contract Views are ADTs (1)

```
class interface ARRAYED_CONTAINER
feature -- Commands
  assign_at (i: INTEGER; s: STRING)
      -- Change the value at position 'i' to 's'.
    require
      valid_index: 1 <= i and i <= count
    ensure
      size_unchanged:
        imp.count = (old imp.twin).count
      item_assigned:
        imp [i] ~ s
      others_unchanged:
        across
          1 |..| imp.count as j
        all
          j.item /= i implies imp [j.item] ~ (old imp.twin) [j.item]
        end
  count: INTEGER
invariant
  consistency: imp.count = count
end -- class ARRAYED_CONTAINER
```


Why Eiffel Contract Views are ADTs (2)

Even better, the direct correspondence from Eiffel operators to logic allow us to present a *precise behavioural* view.

ARRAYED_CONTAINER

feature -- Commands
assign_at (i: **INTEGER**; s: **STRING**)
-- Change the value at position 'i' to 's'.
require
valid_index: $1 \leq i \leq count$
ensure
size_unchanged: imp.count = (**old** imp.twin).count
item_assigned: imp[i] ~ s
others_unchanged: $\forall j : 1 \leq j \leq imp.count : j \neq i \Rightarrow imp[j] \sim (\textbf{old}\ imp.twin)\ [j]$

feature -- { **NONE** }
-- Implementation of an arrayed-container
imp: ARRAY[STRING]

invariant
consistency: imp.count = count

Beyond this lecture...

1. **Q.** Can you think of more real-life examples of leveraging the power of ***modularity***?
2. Visit the Java API page:

   `https://docs.oracle.com/javase/8/docs/api`

   Visit collection classes which you used in EECS2030 (e.g., `ArrayList`, `HashMap`) and EECS2011.

   Q. Can you identify/justify some example methods which illustrate that these Java collection classes are **not** true ***ADTs*** (i.e., ones with well-specified interfaces)?
3. Constrast with the corresponding library classes and features in EiffelStudio (e.g., `ARRAYED_LIST`, `HASH_TABLE`).

   Q. Are these Eiffel features ***better specified*** w.r.t. obligations/benefits of clients/suppliers?

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Copying Objects
Writing Complete Postconditions

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. 3 Levels of ***Copying Objects***:
   Reference vs. Shallow vs. Deep
2. Use of the `old` ***keyword*** in Postconditions
3. Writing *Complete Postconditions* using logical quantifications:
   Universal ($\forall$) vs. Existential ($\exists$)

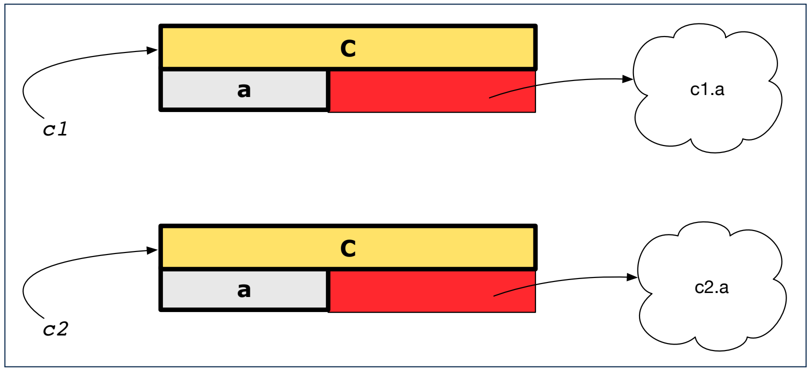
Part 1

Copying Objects

Copying Objects

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

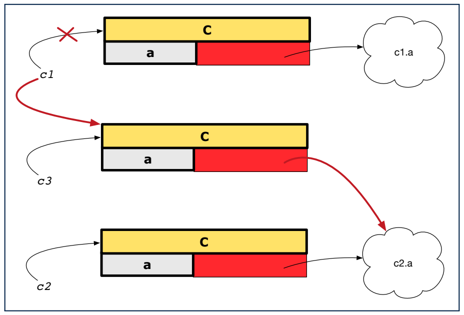
- There is only one attribute a declared in class C.
- c1.a and c2.a are references to objects.



Copying Objects: Shallow Copy

Shallow Copy   *c1* := *c2*.**twin**

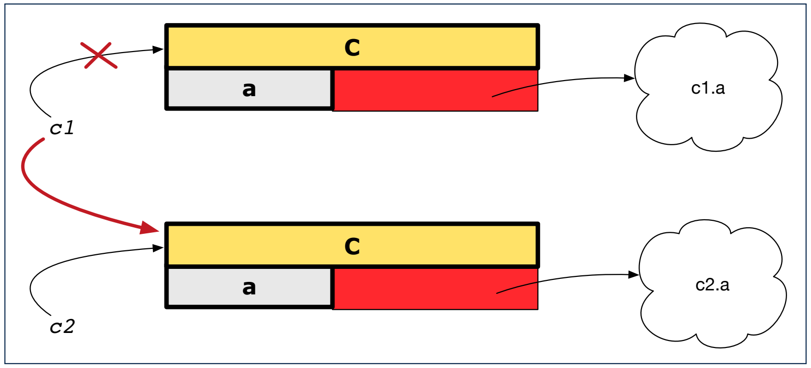
- Create a temporary, behind-the-scene object c3 of type C.
- Initialize each attribute a of c3 via ***reference copy***: *c3.a := c2.a*
- Make a ***reference copy*** of c3: *c1 := c3*
  - ⇒ c1 and c2 ***are not*** pointing to the same object. [*c1 /= c2*]
  - ⇒ c1.a and c2.a ***are*** pointing to the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



Copying Objects: Reference Copy

Reference Copy   *c1* := *c2*

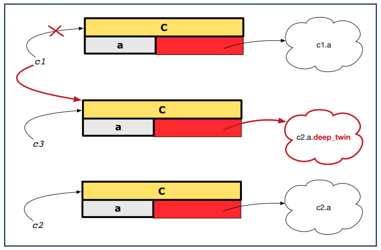
- Copy the address stored in variable c2 and store it in c1.
  - ⇒ Both c1 and c2 point to the same object.
  - ⇒ Updates performed via c1 also visible to c2. [***aliasing***]



Copying Objects: Deep Copy

Deep Copy   *c1* := *c2*.**deep_twin**

- Create a temporary, behind-the-scene object c3 of type C.
- *Recursively* initialize each attribute a of c3 as follows:
  - **Base Case**: a is primitive (e.g., INTEGER). ⇒ *c3.a := c2.a.*
  - **Recursive Case**: a is referenced. ⇒ *c3.a := c2.a*.**deep_twin**
- Make a ***reference copy*** of c3: *c1 := c3*
  - ⇒ c1 and c2 ***are not*** pointing to the same object.
  - ⇒ c1.a and c2.a ***are not*** pointing to the same object.
  - ⇒ ***No aliasing*** occurs at any levels.



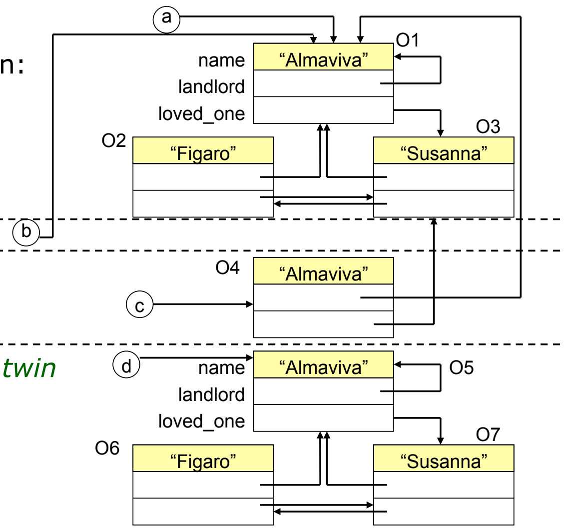
Copying Objects

- Initial situation:
- Result of:

b := *a*

c := *a.twin*

d := *a.deep_twin*



Example: Collection Objects (1)

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

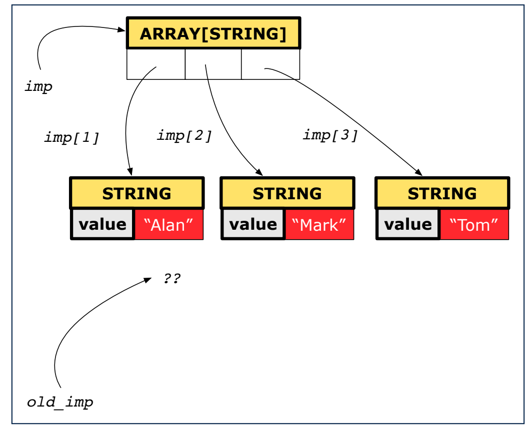
  At *runtime*, that variable stores the *address* of an object of that type (as opposed to storing the object in its entirety).
- Assume the following variables of the same type:

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

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

Example: Collection Objects (2)

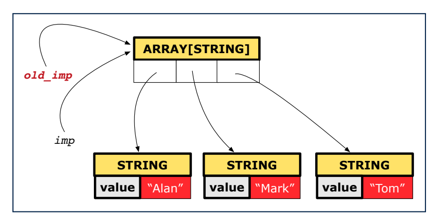
- Variables imp and old_imp store address(es) of some array(s).
- Each “slot” of these arrays stores a STRING object’s address.



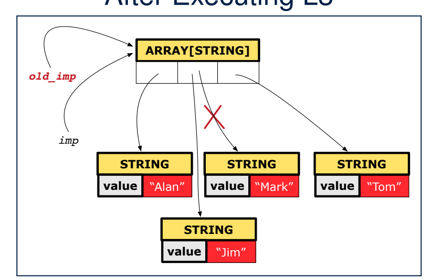
Reference Copy of Collection Object

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

Before Executing L3



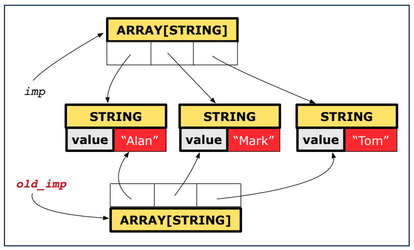
After Executing L3



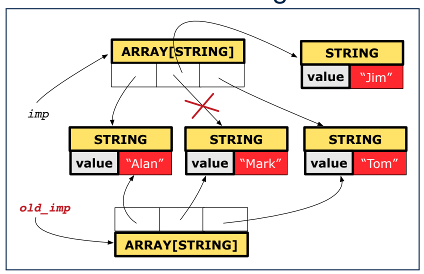
Shallow Copy of Collection Object (1)

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

Before Executing L3



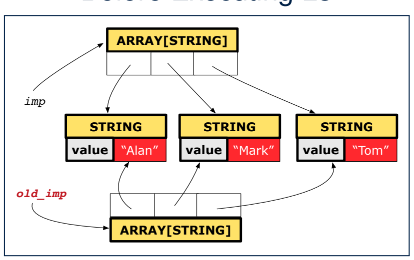
After Executing L3



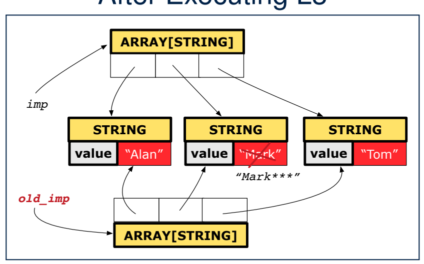
Shallow Copy of Collection Object (2)

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

Before Executing L3



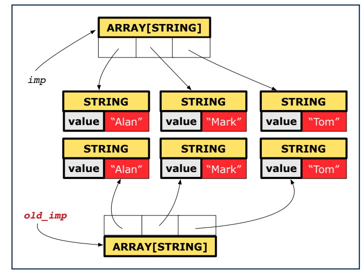
After Executing L3



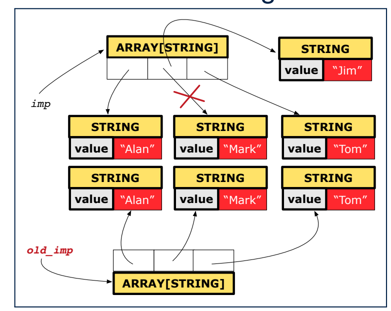
Deep Copy of Collection Object (1)

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

Before Executing L3



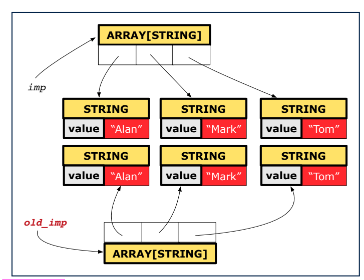
After Executing L3



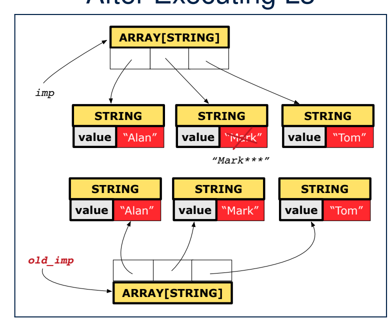
Deep Copy of Collection Object (2)

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

Before Executing L3



After Executing L3



Experiment: Copying Objects

- **Download** the Eiffel project archive (a zip file) here:

  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/codes/copying_objects.zip
- Unzip and compile the project in Eiffel Studio.
- Reproduce the illustrations explained in lectures.

Part 2

Writing Complete Postconditions

How are contracts checked at runtime?

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

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

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

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

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

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

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

    e.g., (**old** ***Current.twin***).*accounts*[*i*].*id* [*old_current_twin := **Current.twin***]
- Right **after** the feature call:
  - The current state of `acc` is called its ***post-state***.
  - Evaluate *post-condition* using both ***current values*** and ***"cached" values*** of attributes and queries.
  - Evaluate *invariant* using ***current values*** of attributes and queries.

When are contracts complete?

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

  e.g., *ARRAY*, *LINKED_LIST* are composite-structured.

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

Account

```
class
  ACCOUNT

inherit
  ANY
    redefine is_equal end

create
  make

feature -- Attributes
  owner: STRING
  balance: INTEGER

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

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

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


Bank

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


Roadmap of Illustrations

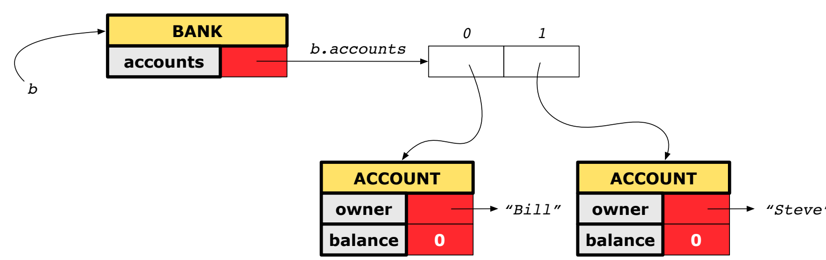
We examine 5 different versions of a command

deposit_on (*n* : *STRING*; *a* : *INTEGER*)

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

Object Structure for Illustration

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



Version 1: Incomplete Contracts, Correct Implementation

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


Test of Version 1

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

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


Test of Version 1: Result

APPLICATION

Note: * indicates a violation test case

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

Version 2: Incomplete Contracts, Wrong Implementation

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

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

Test of Version 2

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

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


Test of Version 2: Result

APPLICATION

Note: * indicates a violation test case

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

Version 3: Complete Contracts with Reference Copy

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


Test of Version 3

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

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

Test of Version 3: Result

APPLICATION

Note: * indicates a violation test case

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

Version 4:
Complete Contracts with Shallow Object Copy

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


Test of Version 4

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

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


Test of Version 4: Result

APPLICATION

Note: * indicates a violation test case

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

Version 5: Complete Contracts with Deep Object Copy

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


Test of Version 5

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

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


Test of Version 5: Result

APPLICATION

Note: * indicates a violation test case

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

Experiment: Complete Postconditions

- **Download** the Eiffel project archive (a zip file) here:
  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/codes/array_math_contract.zip
- Unzip and compile the project in Eiffel Studio.
- Reproduce the illustrations explained in lectures.

Beyond this lecture

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

Index (1)

Index (2)

Index (3)

Index (4)

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. How to ***write*** a generic class (as a ***supplier***)
2. How to ***use*** a generic class (as a ***client***)

Use of Generics

EECS3311 A & E: Software Design
Fall 2020

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 string 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 account 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***.

Index (1)

Abstractions via Mathematical Models

EECS3311 A & E: Software Design
Fall 2020

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Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Creating a ***mathematical abstraction*** for alternative ***implementations***
2. Two design principles: *Information Hiding* and *Single Choice*
3. Review of the basic discrete math (self-guided)

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
```


Design Principles: Information Hiding & Single Choice

- ***Information Hiding*** (IH):
  - Hide supplier's ***design decisions*** that are *likely to change*.
  - Violation of IH means that your design's public API is ***unstable***.
  - *Change of supplier's secrets* should not affect clients relying upon the existing API.
- ***Single Choice Principle*** (SCP):
  - When a ***change*** is needed, there should be ***a single place*** (or ***a minimal number of places***) where you need to make that change.
  - Violation of SCP means that your design contains ***redundancies***.

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

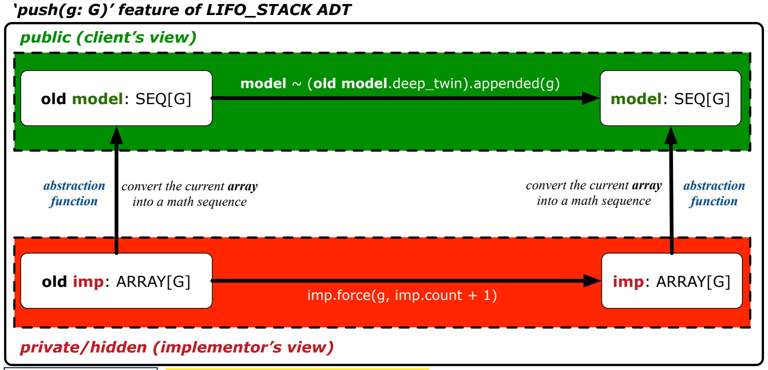
```
class LIFO_STACK[G -> attached ANY] create make
feature -- Abstraction function of the stack ADT
  model: SEQ[G]
feature -- Commands
  push (g: G)
    ensure model ~ (old model.deep_twin).appended(g) end
```

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***:

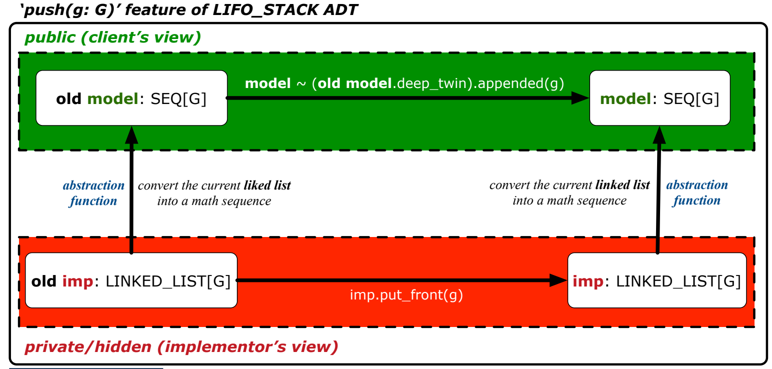
```
model ~ (old model.deep_twin).appended(g)
```


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***:

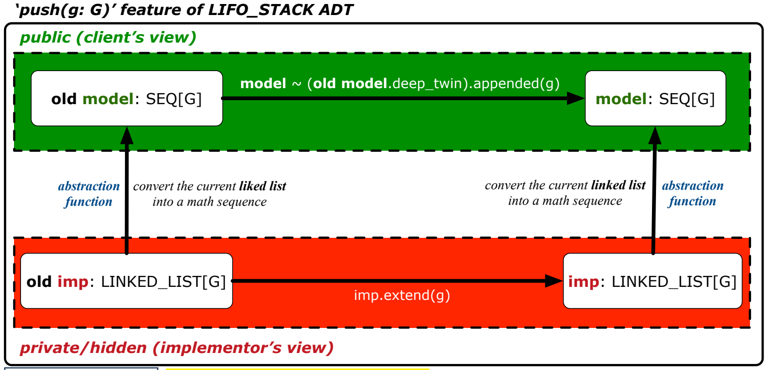
```
model ~ (old model.deep_twin).appended(g)
```

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.

Beyond this lecture . . .

- Familiarize yourself with the features of class `SEQ`.

Index (1)

Drawing a Design Diagram using the Business Object Notation (BON)

EECS3311 A & E: Software Design
Fall 2020

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Index (2)

Learning Objectives

- Purpose of a **Design Diagram**: an *Abstraction* of Your Design
- Architectural Relation: ***Client-Supplier*** vs. ***Inheritance***
- Presenting a class: Compact vs. Detailed
- Denoting a Class or Feature: Deferred vs. Effective

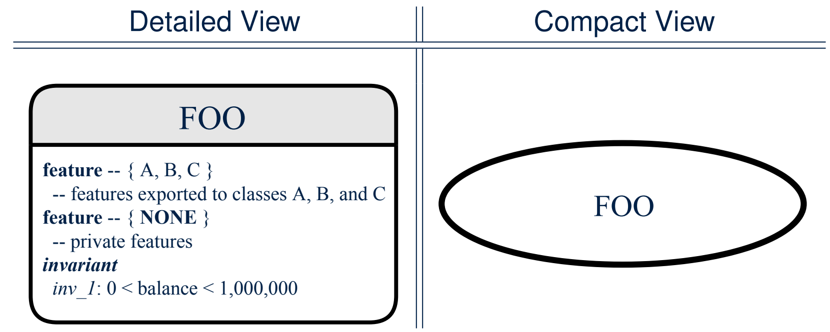
Why a Design Diagram?

- **Source Code** is **not** an appropriate form for communication.
- Use a **Design Diagram** showing *selective* sets of important:
  - clusters (i.e., packages)
  - classes
    [deferred vs. effective]
    [generic vs. non-generic]
  - architectural relations
    [client-supplier vs. inheritance]
  - routines (queries and commands)
    [deferred vs. effective vs. redefined]
  - ***contracts***
    [precondition vs. postcondition vs. class invariant]
- Your design diagram is called an *abstraction* of your system:
  - Being *selective* on what to show, filtering out **irrelevant details**
  - Presenting ***contractual specification*** in a ***mathematical form*** (e.g., ∀ instead of `across ... all ... end`).

Classes: Detailed View vs. Compact View (1)

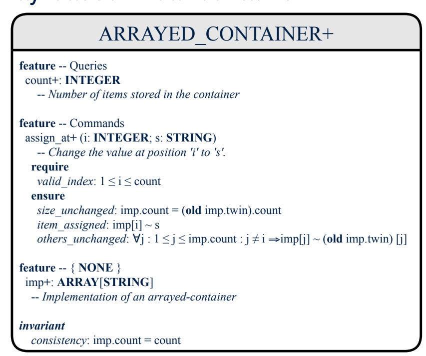
- Detailed view shows a selection of:
  - **features** (queries and/or commands)
  - **contracts** (class invariant and feature pre-post-conditions)
  - Use the detailed view if readers of your design diagram ***should know*** such details of a class.
    e.g., Classes critical to your design or implementation
- Compact view shows only the class name.
  - Use the compact view if readers ***should not be bothered with*** such details of a class.
    e.g., Minor "helper" classes of your design or implementation
    e.g., Library classes (e.g., `ARRAY`, `LINKED_LIST`, `HASH_TABLE`)

Classes: Detailed View vs. Compact View (2)



Contracts: Mathematical vs. Programming

- When presenting the detailed view of a class, you should include *contracts* of features which you judge as ***important***.
- Consider an array-based linear container:

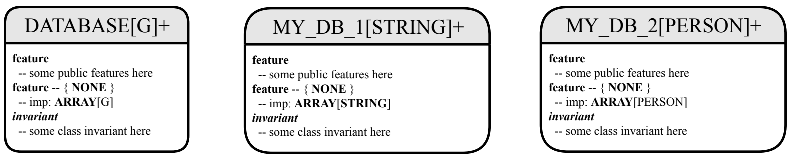


- A ***tag*** should be included for each contract.
- Use ***mathematical*** symbols (e.g., ∀, ∃, ≤) instead of ***programming*** symbols (e.g., `across ... all ...`, `across ... some ...`, `<=`).

Classes: Generic vs. Non-Generic

- A class is *generic* if it declares **at least one** type parameters.
  - Collection classes are generic: `ARRAY[G]`, `HASH_TABLE[G, H]`, *etc.*
  - Type parameter(s) of a class may or may not be ***instantiated***:

  - If necessary, present a generic class in the detailed form:



- A class is *non-generic* if it declares **no** type parameters.

Deferred vs. Effective

Deferred means ***unimplemented*** (≈ **abstract** in Java)

Effective means ***implemented***

Classes: Deferred vs. Effective

- A ***deferred class*** has **at least one** feature ***unimplemented***.
  - A *deferred class* may only be used as a ***static*** type (for declaration), but cannot be used as a ***dynamic*** type.
  - e.g., By declaring `list: LIST[INTEGER]` (where `LIST` is a ***deferred*** class), it is invalid to write:
    - `create list.make`
    - `create {LIST[INTEGER]} list.make`
- An ***effective class*** has **all** features ***implemented***.
  - An *effective class* may be used as both ***static*** and ***dynamic*** types.
  - e.g., By declaring `list: LIST[INTEGER]`, it is valid to write:
    - `create {LINKED_LIST[INTEGER]} list.make`
    - `create {ARRAYED_LIST[INTEGER]} list.make`

    where `LINKED_LIST` and `ARRAYED_LIST` are both ***effective*** descendants of `LIST`.

Features: Deferred, Effective, Redefined (1)

A ***deferred feature*** is declared with its ***header*** only (i.e., name, parameters, return type).

- The word "***deferred***" means a descendant class would later implement this feature.
- The resident class of the ***deferred*** feature must also be ***deferred***.

```
deferred class
  DATABASE[G]
feature -- Queries
  search (g: G): BOOLEAN
      -- Does item 'g' exist in database?
    deferred end
end
```

Features: Deferred, Effective, Redefined (2)

- An ***effective feature*** ***implements*** some inherited deferred feature.

```
class
  DATABASE_V1[G]
inherit
  DATABASE[G]
feature -- Queries
  search (g: G): BOOLEAN
      -- Perform a linear search on the database.
    do end
end
```

- A descendant class may still later ***re-implement*** this feature.

Features: Deferred, Effective, Redefined (3)

- A ***redefined feature*** ***re-implements*** some inherited effective feature.

```
class
  DATABASE_V2[G]
inherit
  DATABASE_V1[G]
      redefine search end
feature -- Queries
  search (g: G): BOOLEAN
      -- Perform a binary search on the database.
    do end
end
```

- A descendant class may still later ***re-implement*** this feature.

Classes: Deferred vs. Effective (2.1)

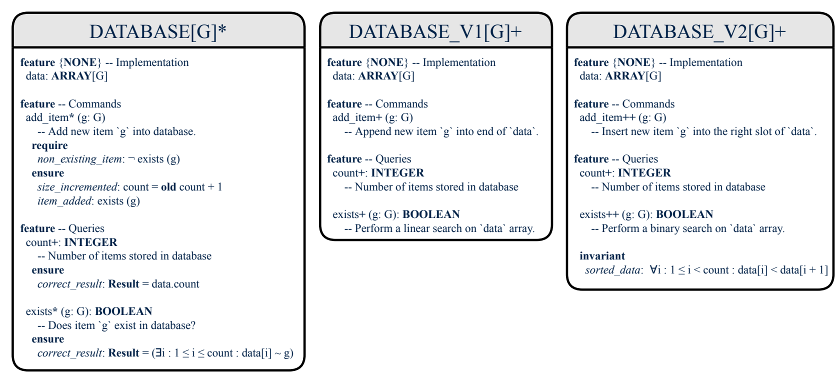
Append a star $\star$ to the name of a ***deferred*** class or feature.
Append a plus **+** to the name of an ***effective*** class or feature.
Append two pluses **++** to the name of a ***redefined*** feature.

- Deferred or effective classes may be in the compact form:

Classes: Deferred vs. Effective (2.2)

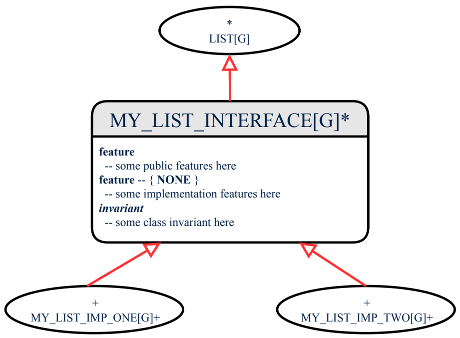
Append a star $\star$ to the name of a ***deferred*** class or feature.
Append a plus **+** to the name of an ***effective*** class or feature.
Append two pluses **++** to the name of a ***redefined*** feature.

- Deferred or effective classes may be in the detailed form:



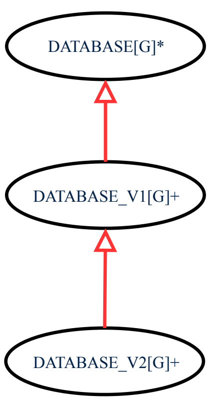
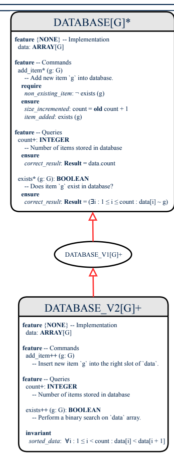
Class Relations: Inheritance (1)

- An inheritance hierarchy is formed using ***red arrows***.
  - Arrow's ***origin*** indicates the ***child***/***descendant*** class.
  - Arrow's ***destination*** indicates the ***parent***/***ancestor*** class.
- You may choose to present each class in an inheritance hierarchy in either the detailed form or the compact form:



Class Relations: Inheritance (2)

More examples (emphasizing different aspects of `DATABASE`):

Inheritance Hierarchy	Features being (Re-)Implemented
	

Class Relations: Client-Supplier (1)

- A client-supplier (CS) relation exists between two classes: one (the ***client***) uses the service of another (the ***supplier***).
- Programmatically, there is CS relation if in class `CLIENT` there is a variable declaration `s1: SUPPLIER`.
  - A variable may be an attribute, a parameter, or a local variable.
- A ***green arrow*** is drawn between the two classes.
  - Arrow's ***origin*** indicates the ***client*** class.
  - Arrow's ***destination*** indicates the ***supplier*** class.
  - Above the arrow there should be a *label* indicating the **supplier name** (i.e., variable name).
  - In the case where supplier is a routine, indicate after the label name if it is deferred (*), effective (+), or redefined (++).

Class Relations: Client-Supplier (2.1)

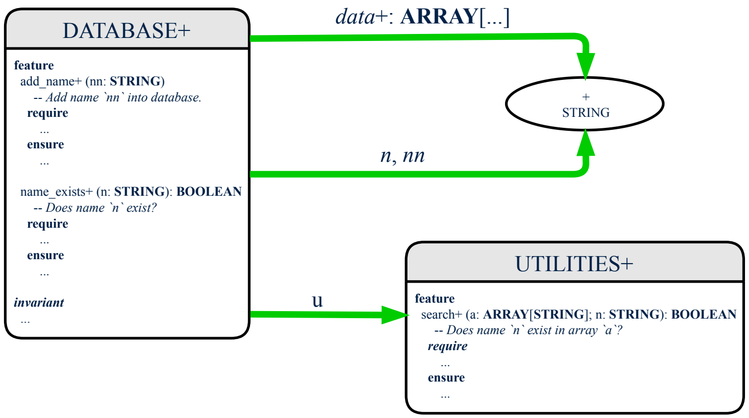
```
class DATABASE
feature {NONE} -- implementation
  data: ARRAY[STRING]
feature -- Commands
  add_name (nn: STRING)
     -- Add name 'nn' to database.
    require ... do ... ensure ... end

  name_exists (n: STRING): BOOLEAN
     -- Does name 'n' exist in database?
    require ...
    local
      u: UTILITIES
    do ... ensure ... end
invariant
  ...
end
```

```
class UTILITIES
feature -- Queries
  search (a: ARRAY[STRING]; n: STRING): BOOLEAN
     -- Does name 'n' exist in array 'a'?
    require ... do ... ensure ... end
end
```

- Query `data: ARRAY[STRING]` indicates two suppliers: `STRING` and `ARRAY`.
- Parameters `nn` and `n` may have an arrow with label nn, n, pointing to the `STRING` class.
- Local variable `u` may have an arrow with label u, pointing to the `UTILITIES` class.

Class Relations: Client-Supplier (2.2.1)

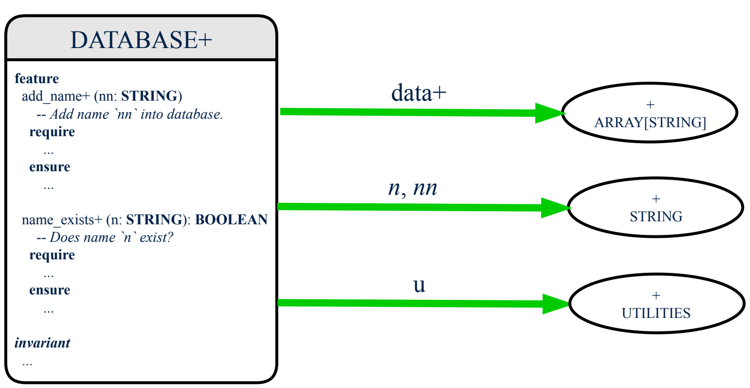
If `STRING` is to be emphasized, label is `data: ARRAY[...]`, where `...` denotes the supplier class `STRING` being pointed to.



Class Relations: Client-Supplier (2.2.2)

If `ARRAY` is to be emphasized, label is `data`.

The supplier's name should be complete: `ARRAY[STRING]`



Class Relations: Client-Supplier (3.1)

Known: The *deferred* class `LIST` has two *effective* descendants `ARRAY_LIST` and `LINKED_LIST`).

- DESIGN ONE:

```
class DATABASE_V1
feature {NONE} -- implementation
  imp: ARRAYED_LIST[PERSON]
... -- more features and contracts
end
```

- DESIGN TWO:

```
class DATABASE_V2
feature {NONE} -- implementation
  imp: LIST[PERSON]
... -- more features and contracts
end
```

Question: Which design is better? [DESIGN TWO]

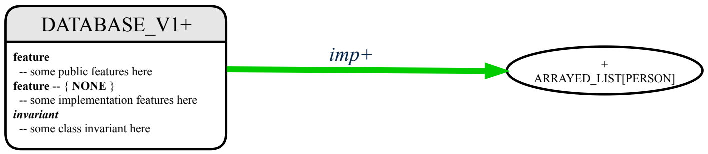
Rationale: Program to the ***interface***, not the ***implementation***.

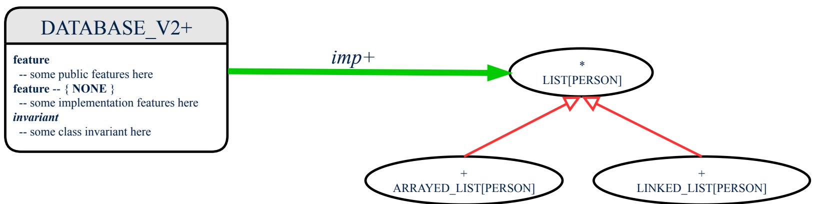
Class Relations: Client-Supplier (3.2.1)

We may focus on the `PERSON` supplier class, which may not help judge which design is better.

Class Relations: Client-Supplier (3.2.2)

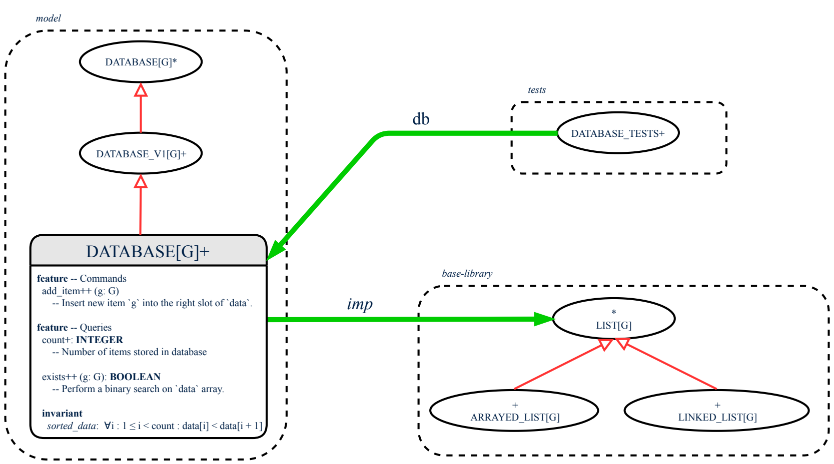
Alternatively, we may focus on the `LIST` supplier class, which in this case helps us judge which design is better.





Clusters: Grouping Classes

Use *clusters* to group classes into logical units.



Beyond this lecture

- Your Lab0 introductory tutorial series contains the following classes:
  - BIRTHDAY
  - BIRTHDAY_BOOK
  - TEST_BIRTHDAY
  - TEST_BIRTHDAY_BOOK
  - TEST_LIBRARY
  - BAD_BIRTHDAY_VIOLATING_DAY_SET
  - BIRTHDAY_BOOK_VIOLATING_NAME_ADDED_TO_END

  Draw a ***design diagram*** showing the ***architectural relations*** among the above classes.

Index (1)

Index (2)

Case Study: Abstraction of a Birthday Book

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CHEN-WEI WANG

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Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Asserting Set Equality in Postconditions (Exercise)
2. The basics of discrete math (Self-Guided Study)
   `FUN` is a `REL`, but not vice versa.
3. Creating a ***mathematical abstraction*** for a birthday book
4. Using commands and queries from two `mathmodels` classes: `REL` and `FUN`

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.

$$S_1 = S_2 \iff S_1 \subseteq S_2 \wedge S_2 \subseteq S_1$$

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

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

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.

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

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

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

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

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

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 $S_1, S_2, \ldots, S_n$, a *cross product* of theses sets is a set of n-tuples.

Each *n-tuple* $(e_1, e_2, \ldots, e_n)$ contains n elements, each of which a member of the corresponding set.

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

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

$$\begin{aligned} & \{a, b\} \times \{2, 4\} \times \{\$, \&\} \\ = \; & \{\ (e_1, e_2, e_3) \mid e_1 \in \{a, b\} \wedge e_2 \in \{2, 4\} \wedge e_3 \in \{\$, \&\}\ \} \\ = \; & \{(a, 2, \$), (a, 2, \&), (a, 4, \$), (a, 4, \&), \\ & (b, 2, \$), (b, 2, \&), (b, 4, \$), (b, 4, \&)\} \end{aligned}$$

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

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

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.

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

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

- $S \times T$ [No]
- $(S \times T) - \{(x,y) \mid (x,y) \in S \times T \wedge x = 1\}$ [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*:

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

- 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 $f : S \to T$:

- f is *injective* (or an injection) if f does not map two members of S to the same member of T.

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

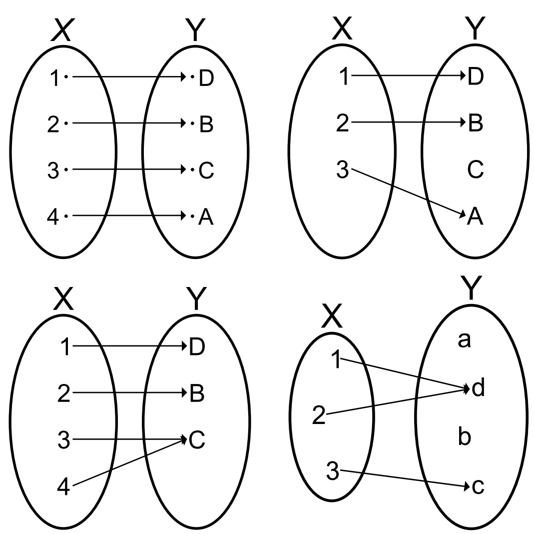
  e.g., Considering an array as a function from integers to objects, being injective means that the array does not contain any duplicates.

- f is *surjective* (or a surjection) if f maps to all members of T.

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

- 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_restrict**ed**
domain_restrict_by	domain_restrict**ed**_by
domain_subtract	domain_subtract**ed**
domain_subtract_by	domain_subtract**ed**_by
range_restrict	range_restrict**ed**
range_restrict_by	range_restrict**ed**_by
range_subtract	range_subtract**ed**
range_subtract_by	range_subtract**ed**_by
override	overrid**den**
override_by	overrid**den**_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
```

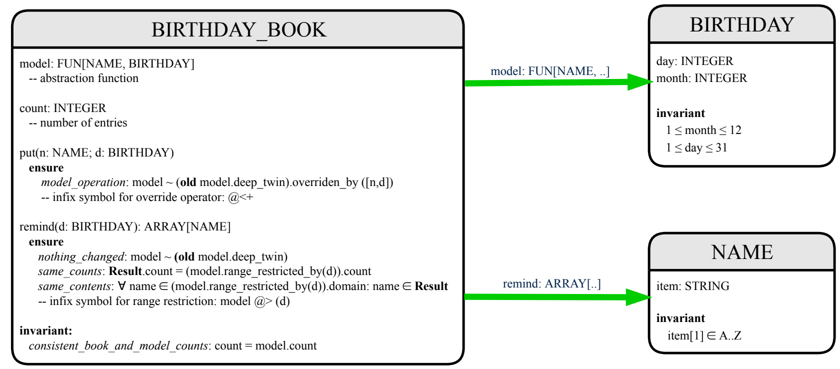
Case Study: A Birthday Book

- 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

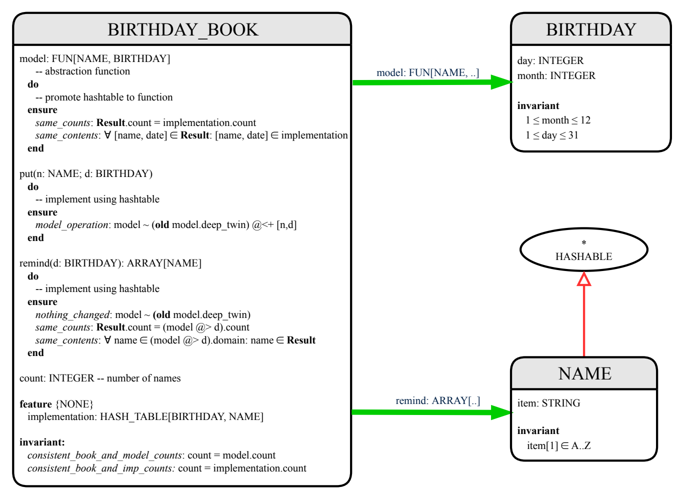
Birthday Book: Decisions

- ***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 *abstraction function* that maps implementation to the math model.

Birthday Book: Design



Birthday Book: Implementation



Beyond this lecture . . .

- Familiarize yourself with the features of class `REL`, `FUN`, and `SET`.
- **Exercise**:
  - Consider an alternative implementation using two linear structures (e.g., here in Java).
  - Implement the design of birthday book covered in lectures.
  - Create another `LINEAR_BIRTHDAY_BOOK` class and modify the implementation of abstraction function accordingly. Do all contracts still pass? What should change? What remain unchanged?

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Design Pattern: Iterator

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Motivating Problem of the Iterator Design Pattern
2. Supplier: Implementing the Iterator Design Pattern
3. Client: Using the Iterator Design Pattern
4. A Challenging Exercise (architecture & generics)

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
```

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
```

Problems?

Iterator Pattern: Motivation (2)

Supplier:

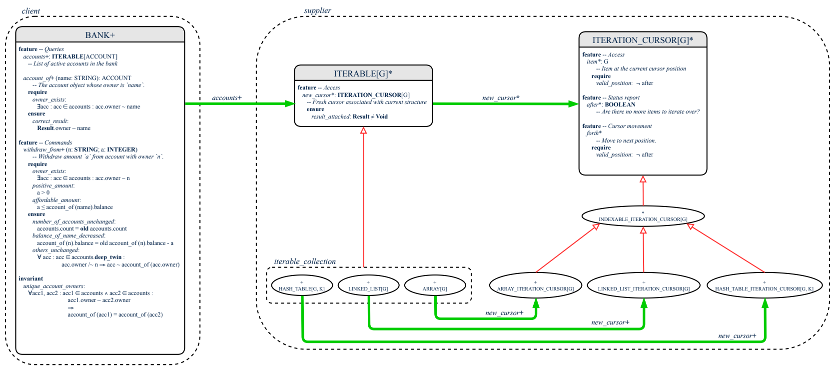
```
class
  CART
feature
  orders: LINKED_LIST[ORDER]
end

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

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
```

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

Iterator Pattern: Architecture



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 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 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!

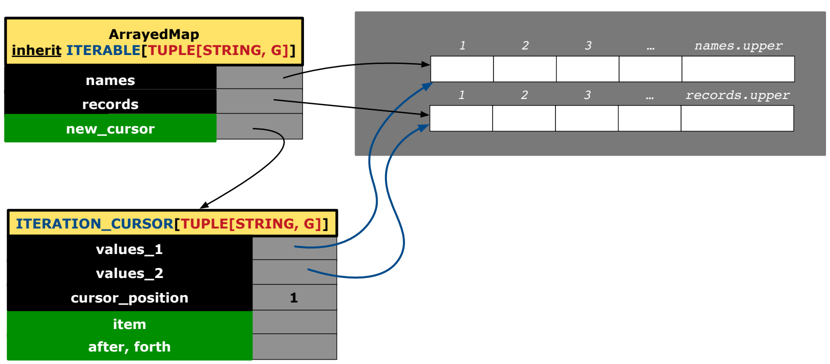
Iterator Pattern: Supplier's Imp. (2.2)

```
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
- Tutorial on Making a Birthday Book (implemented using HASH_TABLE) ITERABLE

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 is item
      all
        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) is i
      all
        accounts [i].id <= accounts [i + 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 cursor := accounts. new_cursor ; max := cursor. item
      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      do
7        across
8          cart is order
9        loop
10         Result := Result + order.price * order.quantity
11       end
12     ensure ??
13   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: LIST[ACCOUNT] -- Q: Can ITERABLE[ACCOUNT] work?
  max_balance: ACCOUNT
      -- Account with the maximum balance value.
    require ??
    local
      max: ACCOUNT
    do
      max := accounts [1]
      across
        accounts is acc
      loop
        if acc.balance > max.balance then
          max := acc
        end
      end
    ensure ??
    end
```


Beyond this lecture ...

- Tutorial Videos on Iterator Pattern
- Exercise: Architecture & Generics

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Singleton Design Pattern

EECS3311 A & E: Software Design
Fall 2020

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Learning Objectives

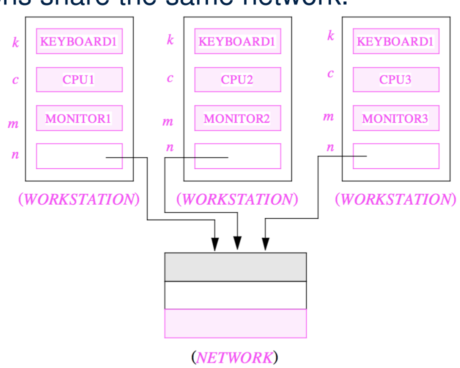
Upon completing this lecture, you are expected to understand:

1. Modeling Concept of ***Expanded Types*** (Compositions)
2. ***Once Routines*** in Eiffel vs. Static Methods in Java
3. Export Status
4. Sharing via ***Inheritance*** (w.r.t. ***SCP*** and ***Cohesion***)
5. *Singleton* Design Pattern

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

- **L5**: object of expanded type is automatically initialized.
- **L10,L12,L13**: no sharing among objects of expanded type.
- **L6,L9,L14**: = compares contents between expanded objects.

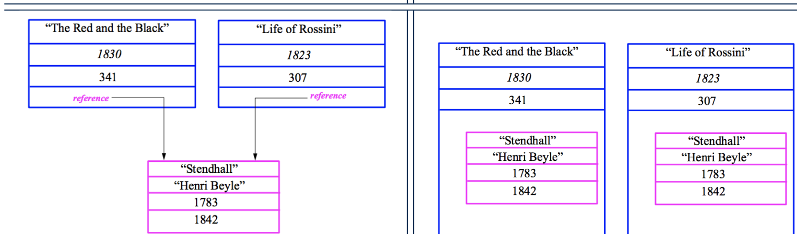
Reference vs. Expanded (1)

- 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?

reference-typed author	***expanded***-typed author



Hyperlinked author page	Physical printed copies

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:

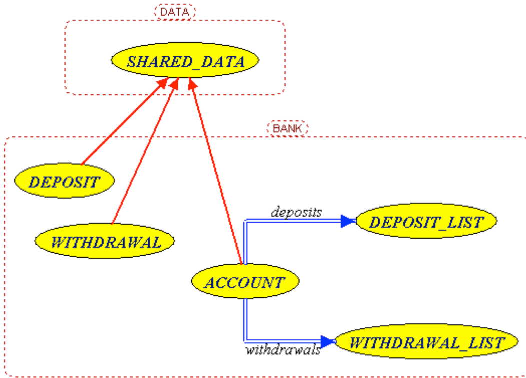
```
class DEPOSIT inherit SHARED_DATA
      -- 'maximum_balance' relevant
end

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 <u>separate</u> 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:

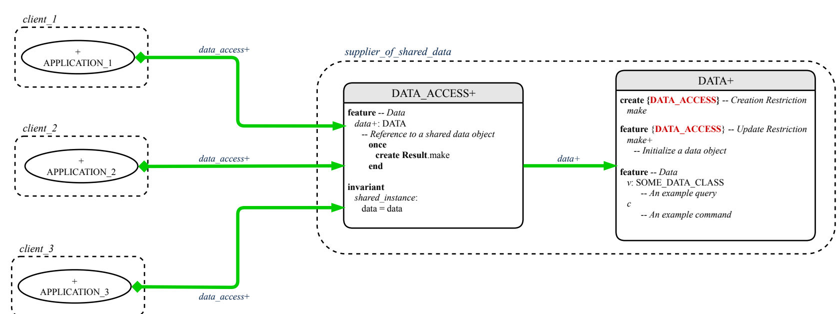
```
class
  ACCOUNT
feature
  data: BANK_DATA
  make (...)
      -- Init. access to bank data.
    local
      data_access: BANK_DATA_ACCESS
    do
      data := data_access.data
      ...
    end
end
```

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 the problem of shared bank data.

Draw it in `draw.io`.

Beyond this lecture

The ***singleton*** pattern is instantiated in the ETF framework:

- ETF_MODEL (***shared data***)
- ETF_MODEL_ACCESS (***exclusive once access***)
- ETF_COMMAND and its effective descendants:

```
deferred class
  ETF_COMMAND
feature -- Attributes
  model: ETF_MODEL
feature {NONE}
  make(...)
    local
      ma: ETF_MODEL_ACCESS
    do
      ...
      model := ma.m
    end
end
```

```
class
  ETF_MOVE
inherit
  ETF_MOVE_INTERFACE
  -- which inherits ETF_COMMAND
feature -- command
  move(...)
    do
      ...
      model.some_routine (...)
      ...
    end
end
```


Index (1)

Index (2)

Eiffel Testing Framework (ETF): Automated Regression & Acceptance Testing

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. ***User Interface***: Concrete vs. ***Abstract***
2. ***Use Case***: Interleaving Model, Events & ***(Abstract) States***
3. ***Acceptance Tests*** vs. Unit Tests
4. *Regression Tests*

Required Tutorial

All technical details of ETF are discussed in this tutorial series:

`https://www.youtube.com/playlist?list=PL5dxAmCmjv 5unIqLB9XiLwBey105y3kI`

Take-Home Message

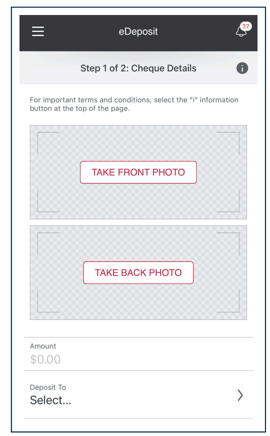
- Your remaining assignments are related to ETF: Lab3 & Project.
- You are no longer just given **partially** implemented classes:
  - Design decisions have already been made for you.
  - You are just to fill in the blanks (`to-do's`).
- ETF is in Eiffel, but try to see beyond what it allows you do:
  1. Design ***your own classes and routines***.
  2. Practice ***design principles***:
     e.g., DbC, modularity, information hiding, single-choice, cohesion.
  3. Practice ***design patterns***:
     e.g., iterator, singleton.
  4. Practice ***acceptance*** testing and ***regression*** testing.

Bank ATM: Concrete User Interfaces

An ATM app has many **concrete** (implemented, functioning) UIs.

PHYSICAL INTERFACE

MOBILE INTERFACE



UI, Model, TDD

- ***Separation of Concerns***
  - The (**Concrete**) User Interface
    Users typically interact with your application via some GUI.
    e.g., web app, mobile app, or desktop app
  - The *Model* (Business Logic)
    Develop an application via classes and features.
    e.g., a bank storing, processing, retrieving accounts & transactions
- ***Test Driven Development*** (***TDD***) In practice:
  - The model should be ***independent*** of the UI or View.
  - Do **not** wait to test the *model* when the **concrete** UI is built.

  ⇒ Test your software as if it was a real app

  way before dedicating to the design of an actual GUI.

  ⇒ Use an ***abstract*** UI (e.g., a cmd-line UI) for this purpose.

Prototyping System with Abstract UI

- For you to quickly *prototype* a working system, you do not need to spend time on developing a elaborate, full-fledged GUI.
- The ***Eiffel Testing Framework*** (***ETF***) allows you to:
  - Generate a starter project from the specification of an ***abstract UI***.
  - Focus on developing the business *model*.
  - Test your business model as if it were a real app.
- **Q**. What is an ***abstract UI***?
  Events ***abstracting*** observable interactions with the concrete GUI (e.g., button clicks, text entering).
- **Q**. Events vs. Features (attributes & routines)?

Events	Features
interactions	computations
external	internal
observable	hidden
acceptance tests	unit tests
users, customers	programmers, developers

Bank ATM: Abstract UI

Abstract UI is the list of **events** ***abstracting*** observable interactions with the concrete GUI (e.g., button clicks, text entering).

```
system bank

new(id: STRING)
  -- create a new bank account for "id"
deposit(id: STRING; amount: INTEGER)
  -- deposit "amount" into the account of "id"
withdraw(id: STRING; amount: INTEGER)
  -- withdraw "amount" from the account of "id"
transfer(id1: STRING; id2: STRING; amount: INTEGER)
  -- transfer "amount" from "id1" to "id2"
```


Bank ATM: Abstract States

Abstract State is a representation of the system:

- ***Including*** relevant details of functionalities under *testing*
- ***Excluding*** other irrelevant details

  e.g., An ***abstract state*** may show each account's owner:

```
{alan, mark, tom}
```

  e.g., An ***abstract state*** may also show each account's balance:

```
{alan: 200, mark: 300, tom: 700}
```

  e.g., An ***abstract state*** may show account's transactions:

```
Account Owner: alan
  List of transactions:
    + deposit (Oct 15): $100
    - withdraw (Oct 18): $50
Account Owner: mark
  List of transactions:
```

Bank ATM: Inputs of Acceptance Tests

An *acceptance test* is a ***use case*** of the system under test, characterized by sequential occurrences of ***abstract events***.

For example:

```
new("alan")
new("mark")
deposit("alan", 200)
deposit("mark", 100)
transfer("alan", "mark", 50)
```


Bank ATM: Outputs of Acceptance Tests (1)

Output from running an ***acceptance test*** is a sequence interleaving ***abstract states*** and ***abstract events***:

$$S_0 \text{->} e_1 \text{->} S_1 \text{->} e_2 \text{->} S_2 \text{->} \ldots$$

where:

- S_0 is the ***initial state***.
- S_i is the ***pre-state*** of event e_{i+1} [$i \geq 0$]
  e.g., S_0 is the pre-state of e_1, S_1 is the pre-state of e_2
- S_i is the ***post-state*** of event e_i [$i \geq 1$]
  e.g., S_1 is the post-state of e_1, S_2 is the post-state of e_2

Bank ATM: Outputs of Acceptance Tests (2)

Consider an example acceptance test output:

```
  {}
->new("alan")
  {alan: 0}
->new("mark")
  {alan: 0, mark: 0}
->deposit("alan", 200)
  {alan: 200, mark: 0}
->deposit("mark", 100)
  {alan: 200, mark: 100}
->transfer("alan", "mark", 50)
  {alan: 150, mark: 150}
```

- ***Initial State***? {}
- What role does the state `{alan: 200, mark: 0}` play?
  - ***Post-State*** of `deposit("alan", 200)`
  - ***Pre-State*** of `deposit("mark", 100)`

Bank ATM: Acceptance Tests vs. Unit Tests

Q. Difference between an ***acceptance test*** and a ***unit test***?

```
  {}
->new("alan")
  {alan: 0}
->deposit("alan", 200)
  {alan: 200}
```

```
test: BOOLEAN
  local acc: ACCOUNT
  do create acc.make("alan")
     acc.add(200)
     Result := acc.balance = 200
  end
```

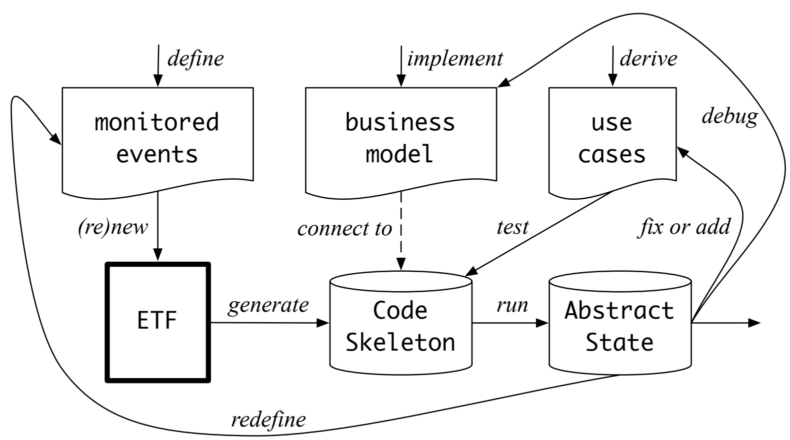
A.

- Writing a ***unit test*** requires knowledge about the ***programming language*** and details of ***implementation***.
  ⇒ Written and run by developers
- Writing an ***acceptance test*** only requires familiarity with the ***abstract UI*** and ***abstract state***.
  ⇒ Written and run by customers [for communication]
  ⇒ Written and run by developers [for testing]

ETF in a Nutshell

- **Eiffel Testing Framework** (**ETF**) facilitates engineers to write and execute ***input-output-based acceptance tests***.
  - ***Inputs*** are specified as traces of events (or sequences).
  - The ***abstract UI*** of the system under development (SUD) is defined by declaring the list of input events that might occur.
  - ***Outputs*** are interleaved states and events logged to the terminal, and their formats may be customized.
- An *executable* ETF project tailored for the SUD can already be generated, using these ***event declarations*** (specified in a plain text file), with a default *business model*.
  - Once the *business model* is implemented, there is a small number of steps to follow for developers to connect it to the generated ETF.
  - Once connected, developers may **re-run** all *acceptance tests* and observe if the expected state effects occur.

Workflow: Develop-Connect-Test



ETF: Abstract UI and Acceptance Test

Input Grammar

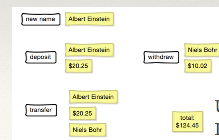
system bank
type NAME = STRING

new(name1: NAME)
-- create a new bank account for "id"

deposit(name1: NAME; amount: VALUE)
-- deposit "amount" into the account of "id"

withdraw(name1: NAME; amount: VALUE)
-- withdraw "amount" from the account of "id"

transfer(name1: NAME; name2: NAME; amount: VALUE)
-- transfer "amount" from "id1" to "id2"

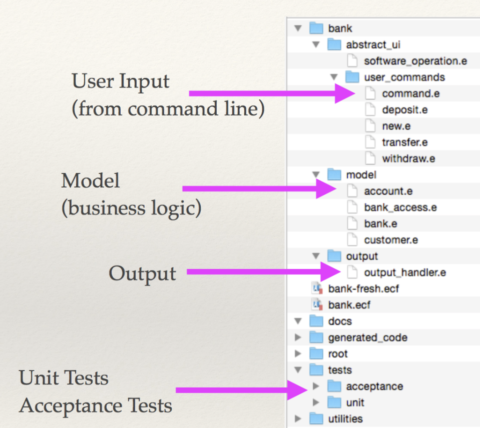


User Interface

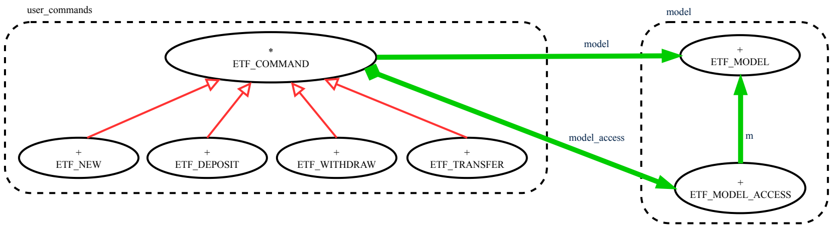
```
%bank -b at1.txt
 init
->new("Steve")
name: Steve, balance: 0.00
->new("Bill")
name: Bill, balance: 0.00
name: Steve, balance: 0.00
->deposit("Steve",520)
name: Bill, balance: 0.00
name: Steve, balance: 520.00
->new("Pam")
name: Bill, balance: 0.00
name: Pam, balance: 0.00
name: Steve, balance: 520.00
->deposit("Bill",100)
name: Bill, balance: 100.00
name: Pam, balance: 0.00
name: Steve, balance: 520.00
->withdraw("Steve",20)
name: Bill, balance: 100.00
name: Pam, balance: 0.00
name: Steve, balance: 500.00
```


ETF: Generating a New Project

etf -new bank.input.txt <directory>



ETF: Architecture



- Classes in the `model` cluster are hidden from the users.
- All commands reference to the same model (bank) instance.
- When a user's request is made:
  - A ***command object*** of the corresponding type is created, which invokes relevant feature(s) in the `model` cluster.
  - Updates to the model are published to the output handler.

ETF: Implementing an Abstract Command

```
class
  ETF_DEPOSIT
inherit
  ETF_DEPOSIT_INTERFACE
    redefine deposit end
create
  make
feature -- command
  deposit(id: STRING ; amount: REAL_64)
    do
      if not model.has_user (id) then
        -- Set some error message
      elseif not amount <= model.get_balance (id)  then
        -- Set some other error message
      else
        -- perform some update on the model state
        model.deposit (id, amount)
      end
      -- Publish model update
      etf_cmd_container.on_change.notify ([Current])
    end
end
```


Beyond this lecture

The ***singleton*** pattern is instantiated in the ETF framework:

- `ETF_MODEL` (***shared data***)
- `ETF_MODEL_ACCESS` (***exclusive once access***)
- `ETF_COMMAND` and its effective descendants:

```
deferred class
  ETF_COMMAND
feature -- Attributes
  model: ETF_MODEL
feature {NONE}
  make(...)
    local
      ma: ETF_MODEL_ACCESS
    do
      ...
      model := ma.m
    end
end
```

```
class
  ETF_DEPOSIT
inherit
  ETF_DEPOSIT_INTERFACE
  -- which inherits ETF_COMMAND
feature -- command
  deposit(...)
    do
      ...
      model.some_routine (...)
      ...
    end
end
```


Index (1)

Index (2)

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Design Attempts without Inheritance (w.r.t. Cohesion, SCP)
2. Using Inheritance for Code Reuse
3. Static Type & Polymorphism
4. Dynamic Type & Dynamic Binding
5. Type Casting
6. Polymorphism & Dynamic Binding:
   Routine Arguments, Routine Return Values, Collections

Inheritance

Readings: OOSCS2 Chapters 14 – 16

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

YORK UNIVERSITÉ UNIVERSITY

Aspects of Inheritance

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

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.

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
```


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: 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*

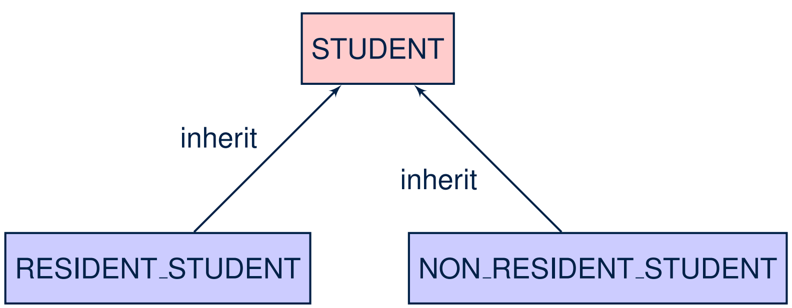
No Inheritance: A Collection of Various Kinds of Students

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
```

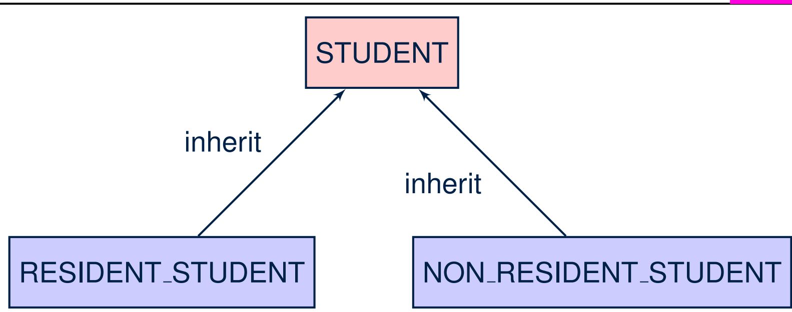
- **L3**: `RESIDENT_STUDENT` inherits all features from `STUDENT`.
- There is no need to repeat the `register` command
- **L14**: *Precursor* returns the value from query `tuition` in `STUDENT`.

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*.

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");
```

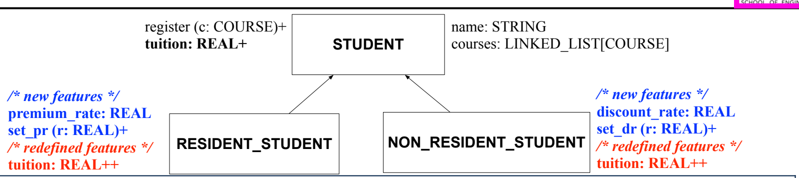
- In Eiffel:

```
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)

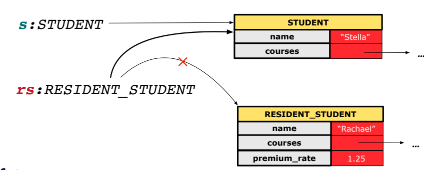
```
1 local
2   s: STUDENT
3   rs: RESIDENT_STUDENT
4 do
5   create s.make ("Stella")
6   create rs.make ("Rachael")
7   rs.set_pr (1.25)
8   s := rs /* Is this valid? */
9   rs := s /* Is this valid? */
```

- 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*:

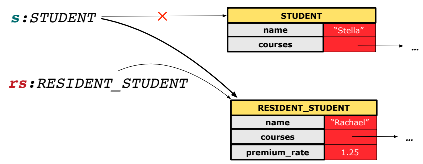


- ***rs*** declared of type RESIDENT_STUDENT
  ∴ calling ***rs***.*set_pr(1.50)* can be expected.
- ***rs*** is now pointing to a STUDENT object.
- Then, what would happen to ***rs***.*set_pr(1.50)*?
  CRASH ∵ ***rs***.premium_rate is *undefined*!!

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*:



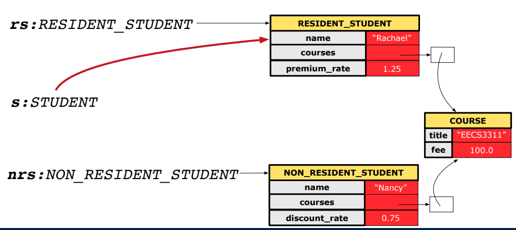
- Since **s** is declared of type `STUDENT`, a subsequent call *s.set_pr (1.50)* is *never* expected.
- **s** is now pointing to a `RESIDENT_STUDENT` object.
- Then, what would happen to *s.tuition*?

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

Dynamic Binding: Intuition (1)

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

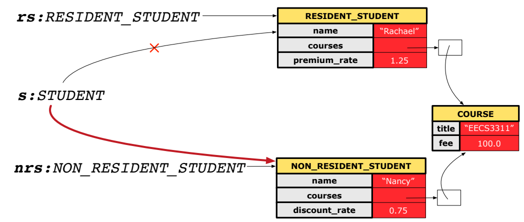
After `s := rs` (**L7**), `s` points to a `RESIDENT_STUDENT` object.
⇒ Calling `s.tuition` applies the `premium_rate`.



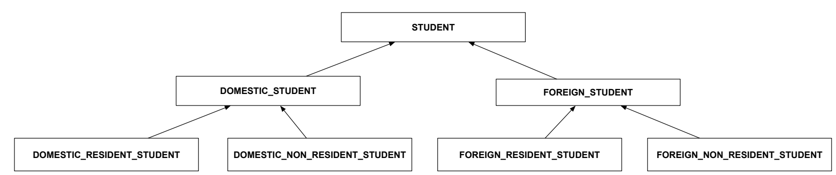
Dynamic Binding: Intuition (2)

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

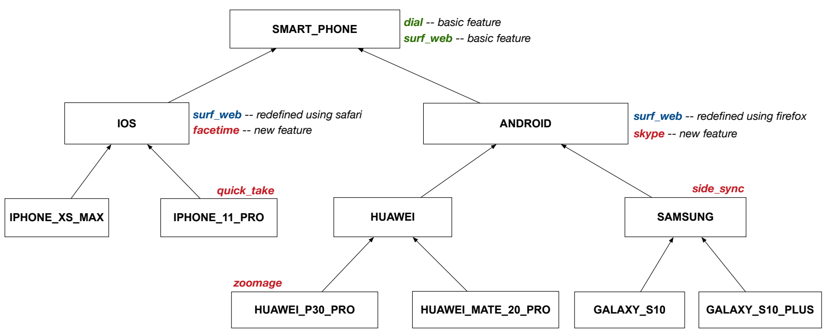
After `s:=nrs` (**L8**), `s` points to a `NON_RESIDENT_STUDENT` object.
⇒ Calling `s.tuition` applies the `discount_rate`.



Multi-Level Inheritance Architecture (1)



Multi-Level Inheritance Architecture (2)



Inheritance Forms a Type Hierarchy

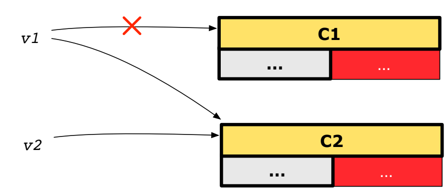
- A (data) *type* denotes a set of related *runtime values*.
  - Every *class* can be used as a type: the set of runtime *objects*.
- Use of *inheritance* creates a *hierarchy* of classes:
  - (Implicit) Root of the hierarchy is `ANY`.
  - Each `inherit` declaration corresponds to an upward arrow.
  - 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 `IPHONE_XS_MAX` or `IPHONE_11_PRO`.
   - ∵ 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 `SMART_PHONE`, 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 approximately the same as 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)

- `check attached {C} y then ... end` *always compiles*
- What if C is not an **ancestor** of y's ***DT***?

  ⇒ A ***runtime*** assertion violation occurs!

  ∵ y's ***DT*** cannot fulfill the expectation of C.

Notes on Type Cast (2)

- Given **v** of static type *ST*, it is ***violation-free*** 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 create an *alias* of the object pointed by **v**, with the new ***static type*** *C*.

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

```
my_phone: IOS
create {IPHONE_11_PRO} my_phone.make
  -- can only call features defined in IOS on myPhone
  -- dial, surf_web, facetime ✓  quick_take, skype, side_sync, zoomage ×
check attached {SMART_PHONE} my_phone as sp then
  -- can now call features defined in SMART_PHONE on sp
  -- dial, surf_web ✓  facetime, quick_take, skype, side_sync, zoomage ×
end
check attached {IPHONE_11_PRO} my_phone as ip11_pro then
  -- can now call features defined in IPHONE_11_PRO on ip11_pro
  -- dial, surf_web, facetime, quick_take ✓  skype, side_sync, zoomage ×
end
```

Notes on Type Cast (3)

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 {HUAWEI} mine.make
   -- ST of mine is ANDROID; DT of mine is HUAWEI
   check attached {SMART_PHONE} mine as sp then ... end
   -- ST of sp is SMART_PHONE; DT of sp is HUAWEI
   check attached {HUAWEI} mine as huawei then ... end
   -- ST of huawei is HUAWEI; DT of huawei is HUAWEI
   check attached {SAMSUNG} mine as samsung then ... end
   -- Assertion violation
   -- ∵ SAMSUNG is not ancestor of mine's DT (HUAWEI)
   check attached {HUAWEI_P30_PRO} mine as p30_pro then ... end
   -- Assertion violation
   -- ∵ HUAWEI_P30_PRO is not ancestor of mine's DT (HUAWEI)
end
```


Polymorphism: Routine Call Parameters

```
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: Routine Call Arguments

```
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         sms.get_student(1).tuition = 750
12     and sms.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 Eiffel code being executed at runtime*

  e.g., which version of the routine 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	Always compiles
check attached {C} y **as** temp **then** x := temp **end**	C a **descendant** of x's ***ST***
check attached {C} y **as** temp **then** x.f(temp) **end**	Feature f defined in x's ***ST*** C a **descendant** of f's parameter's ***ST***

Even if **check attached** {C} y **then** ... **end** always compiles,

a runtime assertion error occurs if C is not an **ancestor** of y's ***DT***!

Beyond this lecture . . .

- ***Written Notes***: Static Types, Dynamic Types, Type Casts
  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/notes/EECS3311_F20_Notes_Static_Types_Cast.pdf
- ***Recommended Exercise 1***:
  Expand the student inheritance design (here) to reproduce the various fragments of polymorphism and dynamic binding.
- ***Recommended Exercise 2***:
  Create a new project (using eiffel-new) to reproduce the various fragments related to the running example of smart phones.

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Learning Objectives

Upon completing this lecture, you are expected to understand:

1. A ***general*** collection `ARRAY[ANY]`: storage vs. retrieval
2. A ***generic*** collection `ARRAY[G]`: storage vs. retrieval
3. Generics vs. Inheritance

Generics

EECS3311 A & E: Software Design
Fall 2020

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?

```
birthday: DATE; phone_number: STRING
b: BOOK; is_wednesday: BOOLEAN
create {BOOK} b.make
phone_number := "416-677-1010"
b.add ("SuYeon", phone_number)
create {DATE} birthday.make(1975, 4, 10)
b.add ("Yuna", birthday)
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)

Say a client stores 100 distinct 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.
if attached {C1} b.get("Jim") as c1 then
  c1.f1
... -- cases for C2 to C99
elseif 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:

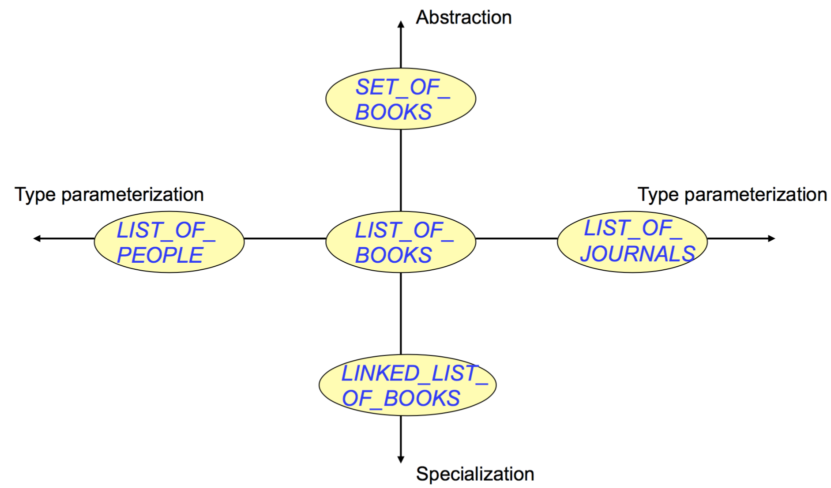
```
class DATABASE_TABLE[K, V]
  imp: DICTIONARY[V, K]
end
```

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

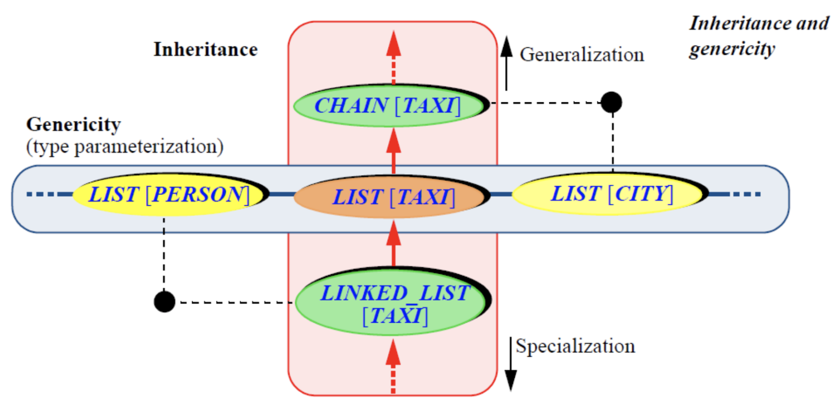
```
class STUDENT_BOOK[V]
  imp: DICTIONARY[V, STRING]
end
```

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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The State Design Pattern

Readings: OOSC2 Chapter 20

YORK UNIVERSITÉ UNIVERSITY

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Learning Objectives

Upon completing this lecture, you are expected to understand:

1. Motivating Problem: ***Interactive*** Systems
2. First Design Attempt: Assembly Style
3. Second Design Attempt: ***Hierarchical***, Procedural Sylte
4. *Template* & *State* Design Patterns: OO, ***Polymorphic***

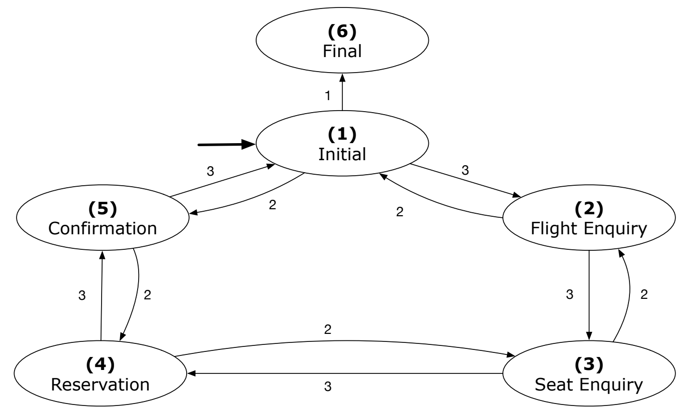
Motivating Problem

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.

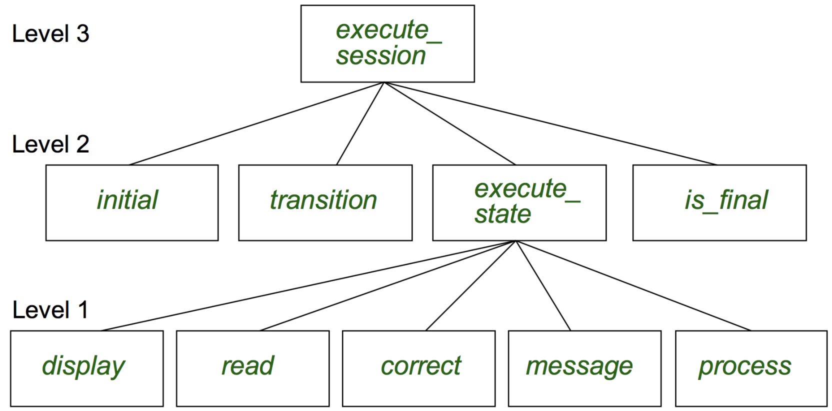
Src State \ Choice	1	2	3
1 (Initial)	6	5	2
2 (Flight Enquiry)	–	1	3
3 (Seat Enquiry)	–	2	4
4 (Reservation)	–	3	5
5 (Confirmation)	–	4	1
6 (Final)	–	–	–

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?

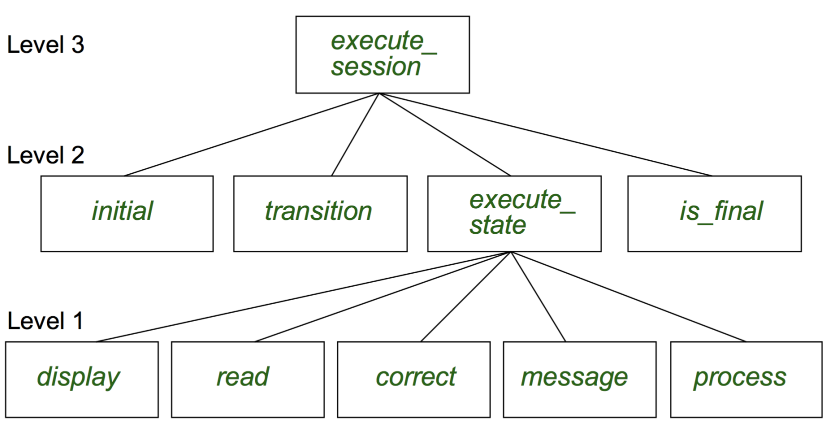
Hierarchical Solution: State Handling (3)

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

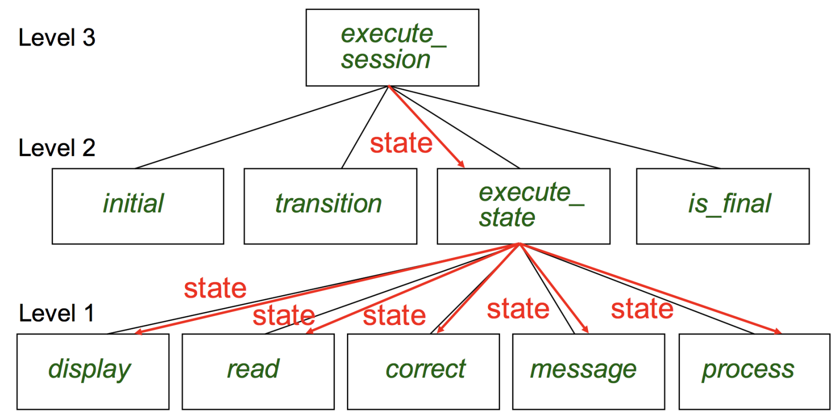
```
display(current_state: INTEGER)
  require
    valid_state: 1 ≤ current_state ≤ 6
  do
    if current_state = 1 then
      -- Display Initial Panel
    elseif current_state = 2 then
      -- Display Flight Enquiry Panel
    ...
    else
      -- Display Final Panel
    end
  end
```

- 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***

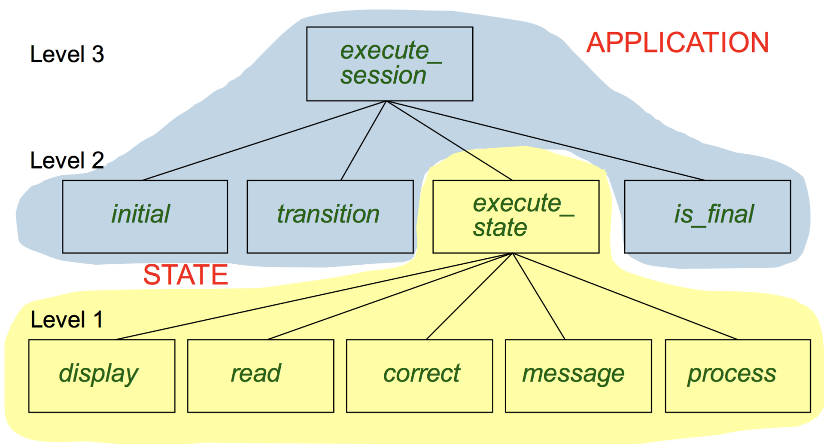
`execute_state`	(*s: INTEGER*)
`display`	(*s: INTEGER*)
`read_answer`	(*s: INTEGER*)
`read_choice`	(*s: INTEGER*)
`correct`	(*s: INTEGER* ; answer: ANSWER)
`process`	(*s: INTEGER* ; answer: ANSWER)
`message`	(*s: INTEGER* ; answer: ANSWER)

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

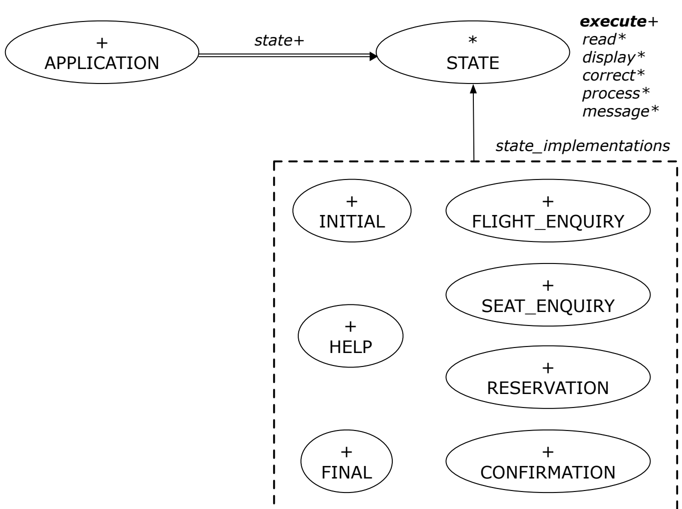
⇒ *Encapsulate* state-related information via a ***STATE*** interface.

⇒ 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
```

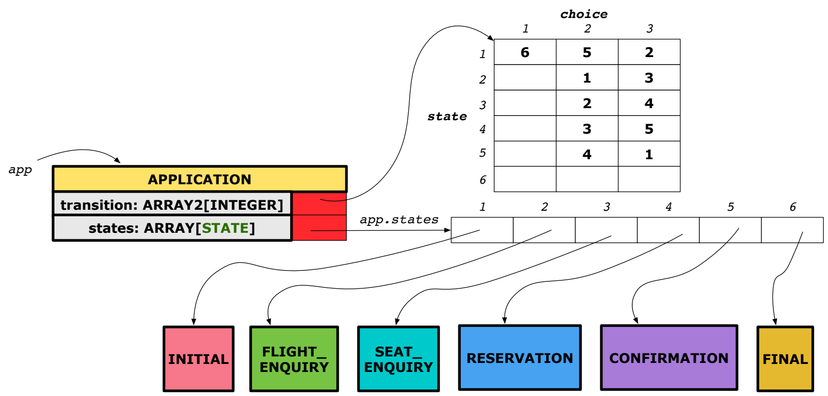

The Template Design Pattern

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



APPLICATION Class (1)

```
class APPLICATION create make
feature {TEST_APPLICATION} -- 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 {TEST_APPLICATION} -- 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 {TEST_APPLICATION} -- 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(create {INITIAL}.make, 4)
```

- 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

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Index (3)

Learning Objectives

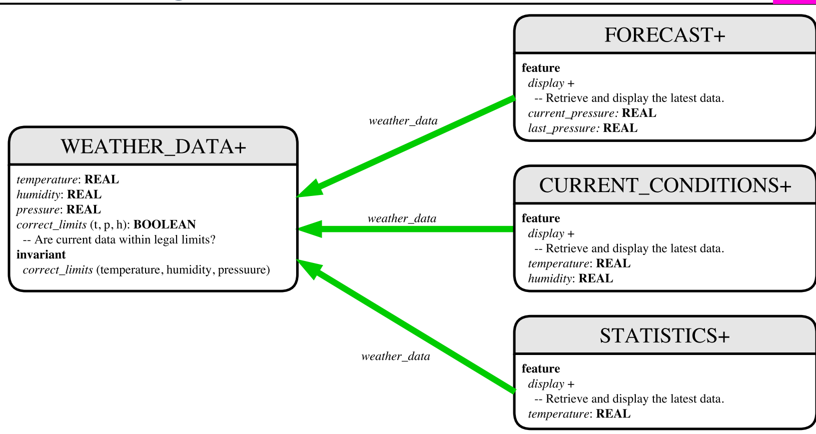
1. Motivating Problem: ***Distributed*** Clients and Servers
2. First Design Attempt: Remote Procedure Calls
3. Second Design Attempt: ***Observer Design Pattern***
4. Third Design Attempt: ***Event-Driven Design*** (Java vs. Eiffel)
5. Use of `agent`

   [≈ C function pointers ≈ C# delegates ≈ Java lambda]

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*:
  - *Forecast*: if expecting for rainy weather due to reduced *pressure*.
  - *Condition*: *temperature* in celsius and *humidity* in percentages.
  - *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(t, p, h)
    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.

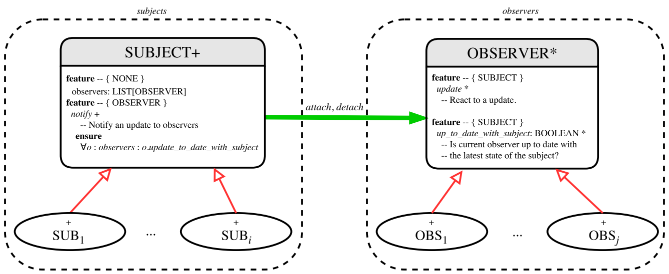
  ⇒ All applications have to periodically initiate updates in order to keep the `display` results up to date.

  ∵ 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 data ***publish/notify*** new changes.

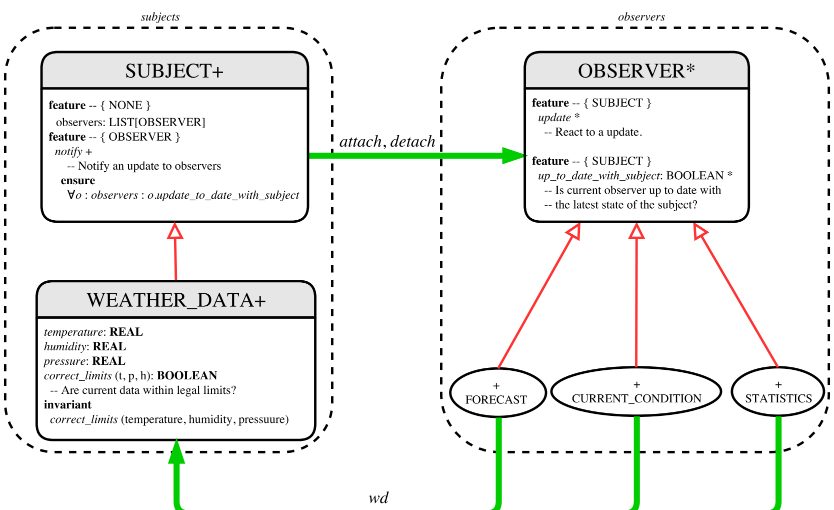
    ⇒ Updates on the application side occur only *when necessary*.

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
```

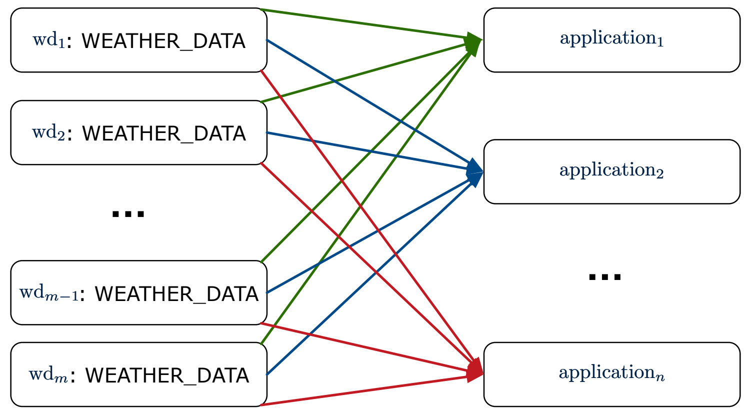
L13: `cc`, `fd`, `sd` make use of "cached" data values.

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)

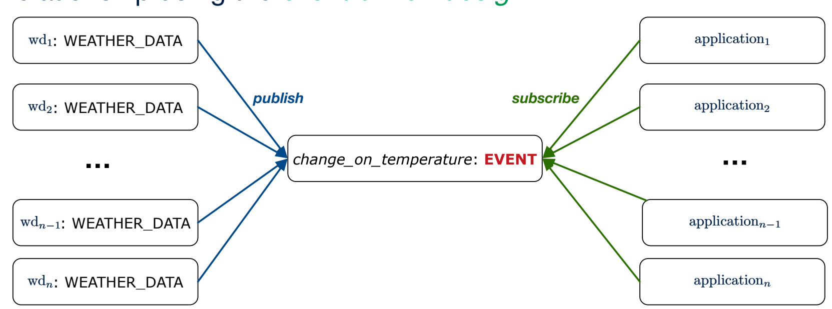
What happens at runtime when building a *many-to-many* relationship using the *observer pattern*?



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)

```java
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)

```java
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)

```eiffel
1  class EVENT [ARGUMENT -> TUPLE]
2  create make
3  feature -- Initialization
4    actions: LINKED_LIST[PROCEDURE[ARGUMENT]]
5    make do create actions.make end
6  feature
7    subscribe (an_action: PROCEDURE[ARGUMENT])
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: ARGUMENT)
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 `ARGUMENT`: any class that instantiates `ARGUMENT` 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)

```eiffel
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[ARGUMENT]]
    ```

- *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*.

Beyond this lecture...

Play with the source code of with the various designs (with an IDE debugger):

- `non_observer.zip` [1st Design Attempt]
- `observer.zip` [Observer Design Pattern]
- `JavaObserverEvent.zip` [Event-Driven Design in Java]
- `observer_event.zip` [Event-Driven Design in Eiffel]

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Subcontracting

Readings: OOSCS2 Chapters 14 – 16

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Aspects of Inheritance

- ***Code Reuse***
- Substitutability
  - ***Polymorphism*** and ***Dynamic Binding***

    [compile-time type checks]
  - *Sub-contracting*

    [runtime behaviour checks]

Learning Objectives

1. ***Preconditions***: require less vs. require more
2. ***Postconditions***: ensure less vs. ensure more
3. Inheritance and Contracts: ***Static Analysis***
4. Inheritance and Contracts: ***Runtime 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`,

$Q_2 : \mathtt{Result} = (i > 0) \wedge (i \textbf{ mod } 2 = 0)$ ***ensures more*** than

$Q_1 : \mathtt{Result} = (i > 0) \vee (i \textbf{ mod } 2 = 0)$

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

Inheritance and Contracts (1)

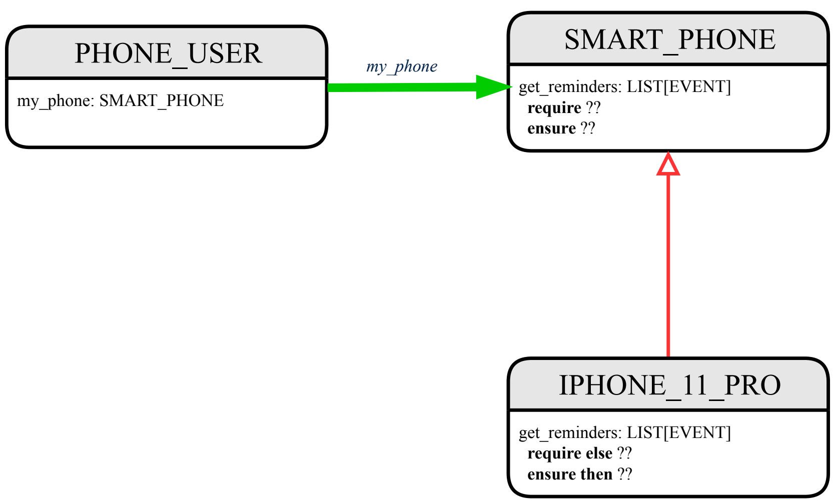
- The fact that we allow *polymorphism*:

```
local my_phone: SMART_PHONE
      i_phone: IPHONE_11_PRO
      samsung_phone: GALAXY_S10_PLUS
      huawei_phone: HUAWEI_P30_PRO
do my_phone := i_phone
   my_phone := samsung_phone
   my_phone := huawei_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_11_PRO
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_11_PRO` are *not suitable*.
($battery\_level \geq 0.1 \Rightarrow battery\_level \geq 0.15$) 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_11_PRO`.

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_11_PRO
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_11_PRO` 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_11_PRO`.

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_11_PRO
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_11_PRO` 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_11_PRO`.

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_11_PRO
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_11_PRO` 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_11_PRO`.

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 postcondition.
- The resulting *runtime assertions checks* are:
  - `original_pre or else new_pre`
    $\Rightarrow$ Clients ***able to satisfy*** *original_pre* will not be shocked.
    $\because$ ***true*** $\vee$ *new_pre* $\equiv$ ***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`
    $\Rightarrow$ ***Failing to gain*** *original_post* will be reported as an issue.
    $\because$ ***false*** $\wedge$ *new_post* $\equiv$ ***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`
  $\because$ ***true*** $\vee$ *new_pre* $\equiv$ ***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`
  $\because$ ***true*** $\wedge$ *new_post* $\equiv$ *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* $\lor$ ***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* $\land$ ***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:

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

  $(vertices.count = 5) \land (vertices.count = 4) \equiv$ ***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* $\lor$ *new_pre* is checked
- *original_post* $\land$ *new_post* is checked

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The Composite Design Pattern

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Learning Objectives

1. Motivating Problem: ***Recursive*** Systems
2. Two Design Attempts
3. Multiple Inheritance
4. Third Design Attempt: ***Composite Design Pattern***
5. Implementing and Testing the Composite Design Pattern

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.

Design Attempt 1: Flaw?

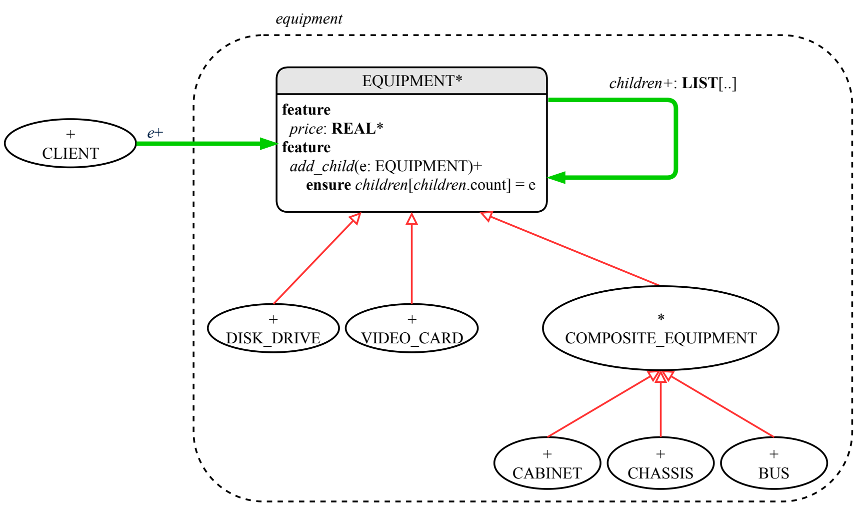
Q: Any flaw of this first design?

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

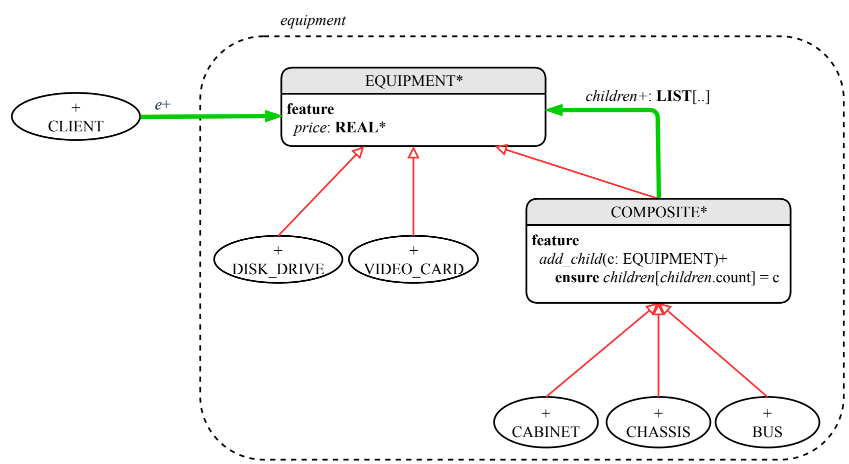
- `children: LIST[EQUIPMENT]`
- `add(child: EQUIPMENT)`

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

Design Attempt 1: Architecture



Design Attempt 2: Architecture



Design Attempt 2: Flaw?

Q: Any flaw of this second design?

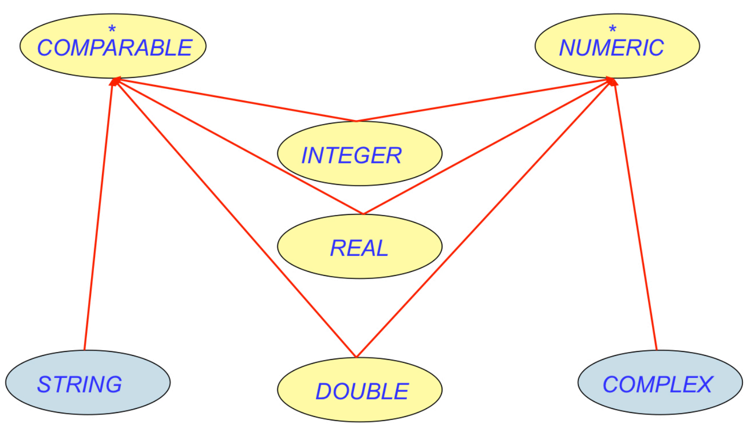
A: Two "composite" features defined at the `COMPOSITE` level:

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

⇒ Multiple instantiations of the composite architecture (e.g., equipments, furnitures) require duplicates of the `COMPOSITE` class.

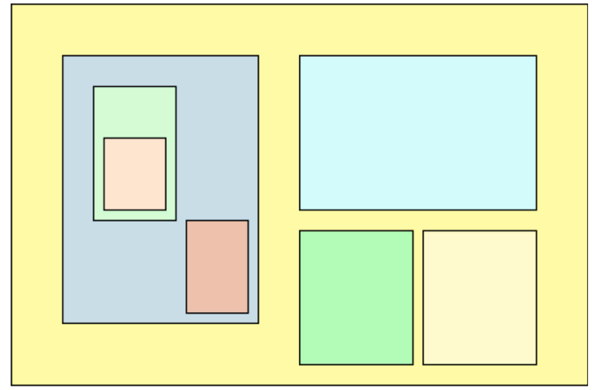
Multiple Inheritance: Combining Abstractions (1)

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 (2.2)

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

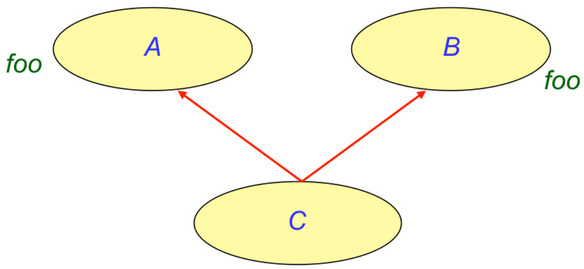
```
class RECTANGLE
  feature -- Queries
    width, height: REAL
    xpos, ypos: REAL
  feature -- Commands
    make (w, h: REAL)
    change_width
    change_height
    move
end
```

```
class TREE[G]
  feature -- Queries
    descendants: ITERABLE[G]
  feature -- Commands
    add (c: G)
       -- Add a child 'c'.
end
```

```
class WINDOW
  inherit
    RECTANGLE
    TREE[WINDOW]
end
```

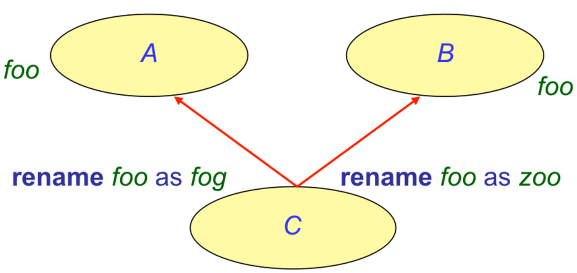
```
test_window: BOOLEAN
  local w1, w2, w3, w4: WINDOW
  do
    create w1.make(8, 6) ; create w2.make(4, 3)
    create w3.make(1, 1) ; create w4.make(1, 1)
    w2.add(w4) ; w1.add(w2) ; w1.add(w3)
    Result := w1.descendants.count = 2
  end
```

MI: Name Clashes



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

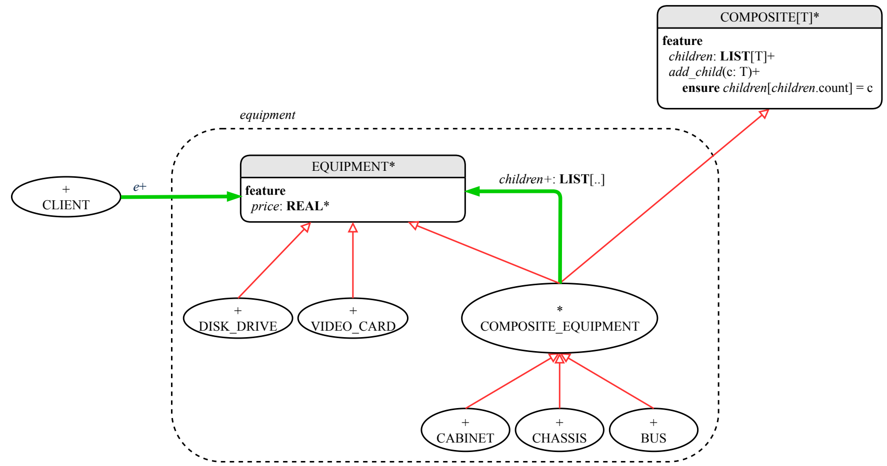
MI: Resolving Name Clashes




```
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	×	✓	✓

The Composite Pattern: Architecture



Implementing the Composite Pattern (1)

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

```
class
  CARD
inherit
  EQUIPMENT
feature {NONE}
  unit_price: REAL
feature
  make (n: STRING; p: REAL)
    do name := n ; unit_price := p end
  price
    do Result := unit_price 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)

```
deferred class
  COMPOSITE_EQUIPMENT
inherit
  EQUIPMENT
  COMPOSITE [EQUIPMENT]
feature
  make (n: STRING)
      -- Child classes will declare this command as a constructor.
    do name := n ; create children.make end
  price : REAL -- price is a query
      -- Sum the net prices of all sub-equipments
    do
      across
        children is c
      loop
        Result := Result + c.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
```


Summay: 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.

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The Visitor Design Pattern

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

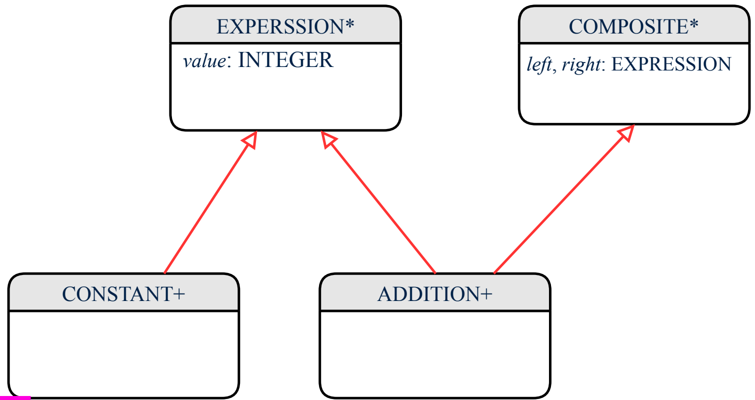
Index (2)

Learning Objectives

1. Motivating Problem: ***Processing*** Recursive Systems
2. First Design Attempt: Cohesion & Single-Choice Principle?
3. Open-Closed Principle
4. Second Design Attempt: ***Visitor Design Pattern***
5. Implementing and Testing the Visitor Design Pattern

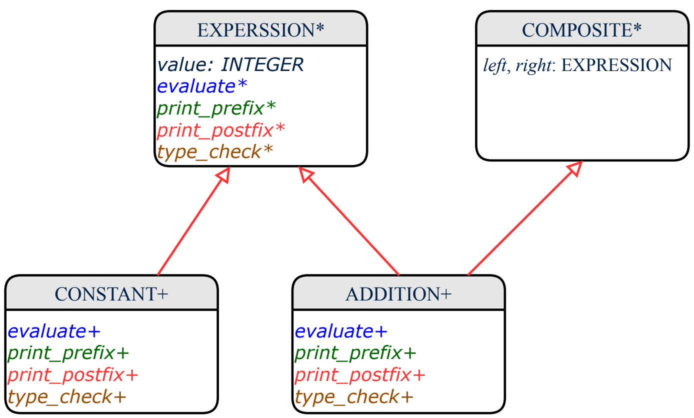
Motivating Problem (1)

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

Visitor Pattern

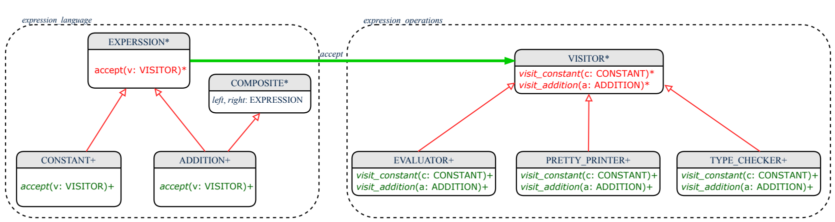
- *Separation of concerns* :
  - Set of language constructs
  - Set of operations

  ⇒ Classes from these two sets are *decoupled* and organized into two separate clusters.
- *Open-Closed Principle (OCP)* : [ALTERNATIVE 2]
  - ***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*** changes often.

Beyond this Lecture. . .

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

  https://www.youtube.com/playlist?list=PL5dxAmCmjv4z5eXGW-ZBgsS2WZTyBHY2
- The Visitor Pattern can be used to facilitate the development of a language compiler:

  https://www.youtube.com/playlist?list=PL5dxAmCmjv4FGYtGzcvBeoS-BobRTJLq

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Learning Objectives

1. Motivating Examples: ***Program Correctness***
2. ***Hoare Triple***
3. ***Weakest Precondition*** (*wp*)
4. Rules of *wp* ***Calculus***
5. Contract of Loops (***invariant*** vs. ***variant***)
6. ***Correctness Proofs*** of Loops

Program Correctness

OOSC2 Chapter 11

EECS3311 A & E: Software Design
Fall 2020

CHEN-WEI WANG

Assertions: Weak vs. Strong

- Describe each assertion as ***a set of satisfying value***.
  $x > 3$ has satisfying values $\{ x \mid x > 3 \} = \{ 4, 5, 6, 7, \ldots \}$
  $x > 4$ has satisfying values $\{ x \mid x > 4 \} = \{ 5, 6, 7, \ldots \}$
- 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

Assertions: Preconditions

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: INTEGER)`,

$P_2 : amount \geq 0$ ***requires less*** than $P_1 : amount > 0$

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

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.

Assertions: Postconditions

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`,

$Q_2 : \textbf{Result} = (i > 0) \wedge (i \textbf{ mod } 2 = 0)$ ***ensures more*** than

$Q_1 : \textbf{Result} = (i > 0) \vee (i \textbf{ mod } 2 = 0)$

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

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 $\boldsymbol{Q}$ and post-condition $\boldsymbol{R}$) 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 and Software Correctness

Consider the *contract view* of a feature *f* (whose body of implementation is **S**) as a Hoare Triple :

$$\{Q\}\ \mathtt{S}\ \{R\}$$

$\boldsymbol{Q}$ is the *precondition* of *f*.
S is the implementation of *f*.
$\boldsymbol{R}$ is the *postcondition* of *f*.

- $\{\textit{true}\}$ S $\{R\}$

  All input values are valid [Most-user friendly]
- $\{\textit{false}\}$ S $\{R\}$

  All input values are invalid [Most useless for clients]
- $\{Q\}$ S $\{\textit{true}\}$

  All output values are valid [Most risky for clients; Easiest for suppliers]
- $\{Q\}$ S $\{\textit{false}\}$

  All output values are invalid [Most challenging coding task]
- $\{\textit{true}\}$ S $\{\textit{true}\}$

  All inputs/outputs are valid (No contracts) [Least informative]

Hoare Logic

- Consider a program **S** with precondition $\boldsymbol{Q}$ and postcondition $\boldsymbol{R}$.
  - $\{Q\}$ 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 $\boldsymbol{Q}$, and then:

    (a) The program **S** terminates.

    (b) Given that program **S** terminates, then it terminates in a state satisfying the postcondition $\boldsymbol{R}$.
- Separation of concerns

  (a) requires a proof of *termination*.

  (b) requires a proof of ***partial** correctness*.

  Proofs of (a) + (b) imply ***total** correctness*.

Proof of Hoare Triple using *wp*

$$\{Q\}\ \mathtt{S}\ \{R\} \equiv Q \Rightarrow wp(S, R)$$

- $wp(S, R)$ is the *weakest precondition for S to establish R*.
  - If $Q \Rightarrow wp(S, R)$, then **any** execution started in a state satisfying $\boldsymbol{Q}$ will terminate in a state **satisfying** $\boldsymbol{R}$.
  - If $Q \not\Rightarrow wp(S, R)$, then **some** execution started in a state satisfying $\boldsymbol{Q}$ will terminate in a state **violating** $\boldsymbol{R}$.
- *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.

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
    ∵ All variables are pre-state values in preconditions
  - We don't write "b_0" in program
    ∵ 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 $?? \Rightarrow wp(\texttt{x := x + 1}, x > x_0)$.

$$\begin{aligned}
& wp(\texttt{x := x + 1}, x > x_0) \\
= & \ \{\texttt{Rule of } wp\texttt{: Assignments}\} \\
& x > x_0[x := x_0 + 1] \\
= & \ \{\texttt{Replacing } x \texttt{ by } x_0 + 1\} \\
& x_0 + 1 > x_0 \\
= & \ \{1 > 0 \texttt{ always true}\} \\
& True
\end{aligned}$$

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 $x = 23$?

$$\{??\}\ \texttt{x := x + 1}\ \{x = 23\}$$

For the above Hoare triple to be ***TRUE***, it must be that $?? \Rightarrow wp(\texttt{x := x + 1}, x = 23)$.

$$
\begin{aligned}
& wp(\texttt{x := x + 1}, x = 23) \\
= & \ \{\textit{Rule of wp: Assignments}\} \\
& x = 23[x := x_0 + 1] \\
= & \ \{\textit{Replacing } x \textit{ by } x_0 + 1\} \\
& x_0 + 1 = 23 \\
= & \ \{\textit{arithmetic}\} \\
& x_0 = 22
\end{aligned}
$$

Any precondition weaker than $x = 22$ is not OK.

wp Rule: Assignments (4) Revisit

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 $n > 13$.

wp Rule: Alternations (1)

$$wp(\textbf{if } B \textbf{ then } S_1 \textbf{ else } S_2 \textbf{ end}, R) = \begin{pmatrix} B \Rightarrow wp(S_1, R) \\ \wedge \\ \neg B \Rightarrow wp(S_2, R) \end{pmatrix}$$

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}
```

$$\{Q\}\ \textbf{if } B \textbf{ then } S_1 \textbf{ else } S_2 \textbf{ end}\ \{R\}$$

$$\iff \begin{pmatrix} \{\ Q \wedge B\ \}\ S_1\ \{\ R\ \} \\ \wedge \\ \{\ Q \wedge \neg B\ \}\ S_2\ \{\ R\ \} \end{pmatrix} \iff \begin{pmatrix} (Q \wedge B) \Rightarrow wp(S_1, R) \\ \wedge \\ (Q \wedge \neg B) \Rightarrow wp(S_2, R) \end{pmatrix}$$

wp Rule: Alternations (3) Exercise

Is this program correct?

$\{x > 0 \wedge y > 0\}$
```
if x > y then
  bigger := x ; smaller := y
else
  bigger := y ; smaller := x
end
```
$\{bigger \geq smaller\}$

$$\left(\begin{array}{l}\{(x > 0 \wedge y > 0) \wedge (x > y)\} \\ \quad \texttt{bigger := x ; smaller := y} \\ \{bigger \geq smaller\}\end{array}\right) \wedge \left(\begin{array}{l}\{(x > 0 \wedge y > 0) \wedge \neg(x > y)\} \\ \quad \texttt{bigger := y ; smaller := x} \\ \{bigger \geq smaller\}\end{array}\right)$$

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:

$$\{Q\} \; S \; \{R\} \equiv Q \Rightarrow wp(S, R)$$

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 $True \Rightarrow wp(\texttt{tmp := x ; x := y ; y := tmp}, x > y)$

$$\begin{array}{ll} & wp(\texttt{tmp := x ; } \boxed{\texttt{x := y ; y := tmp}}, x > y) \\ = & \{\textit{wp rule for seq. comp.}\} \\ & wp(\texttt{tmp := x}, wp(\texttt{x := y ; } \boxed{\texttt{y := tmp}}, x > y)) \\ = & \{\textit{wp rule for seq. comp.}\} \\ & wp(\texttt{tmp := x}, wp(\texttt{x := y}, wp(\texttt{y := tmp}, x > \boxed{y}))) \\ = & \{\textit{wp rule for assignment}\} \\ & wp(\texttt{tmp := x}, wp(\texttt{x := y}, \boxed{x} > tmp)) \\ = & \{\textit{wp rule for assignment}\} \\ & wp(\texttt{tmp := x}, y > \boxed{tmp}) \\ = & \{\textit{wp rule for assignment}\} \\ & y > x \end{array}$$

$\because$ $True \Rightarrow y > x$ 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

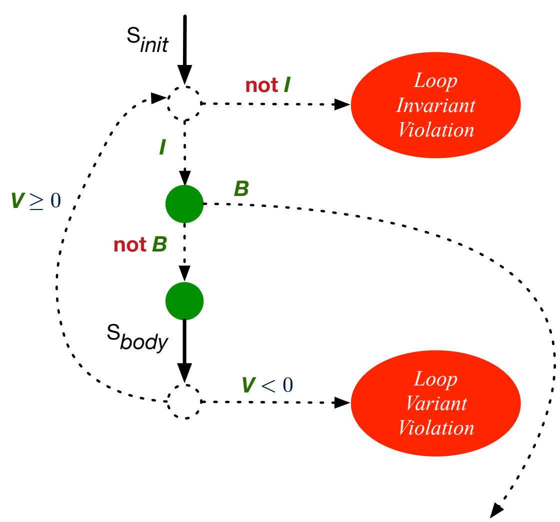
```
from
  S_init
invariant
  invariant_tag: I -- Boolean expression for partial correctness
until
  B
loop
  S_body
variant
  variant_tag: V -- Integer expression for termination
end
```

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)



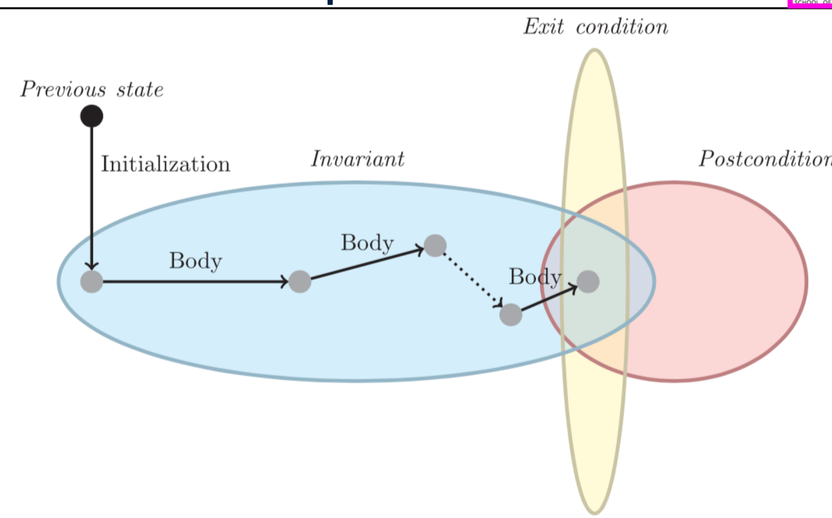
Contracts for Loops: Runtime Checks (2)

```
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***.

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 4th 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***: $\forall j \mid a.lower \leq j < i \bullet Result \geq a[j]$
- ***Loop Variant***: $a.upper - i + 1$
- *Postcondition*: $\forall j \mid a.lower \leq j \leq a.upper \bullet Result \geq a[j]$

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.
    $\{I \land \neg B\}\ S_{body}\ \{I\}$
  - If ready to exit and *LI* I maintained, postcondition R is established.
    $I \land B \Rightarrow R$
- A loop ***terminates*** if:
  - Given *LI* I, and not yet to exit, S_{body} maintains *LV* V as non-negative.
    $\{I \land \neg B\}\ S_{body}\ \{V \geq 0\}$
  - Given *LI* I, and not yet to exit, S_{body} decrements *LV* V.
    $\{I \land \neg B\}\ S_{body}\ \{V < V_0\}$

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:

$$(\forall j \mid a.lower \leq j < i \bullet Result \geq a[j]) \land i > a.upper$$
$$\Rightarrow \forall j \mid a.lower \leq j \leq a.upper \bullet Result \geq a[j]$$

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)

$$\{Q\}\ \mathtt{S}\ \{R\} \Rightarrow \{Q \land P\}\ \mathtt{S}\ \{R\}$$

In order to prove $\{Q \land P\}\ \mathtt{S}\ \{R\}$, it is sufficient to prove a version with a *weaker* precondition: $\{Q\}\ \mathtt{S}\ \{R\}$.

Proof:

- Assume: $\{Q\}\ \mathtt{S}\ \{R\}$
  It's equivalent to assuming: $\boxed{Q} \Rightarrow wp(\mathtt{S}, R)$ **(A1)**
- To prove: $\{Q \land P\}\ \mathtt{S}\ \{R\}$
  - It's equivalent to proving: $Q \land P \Rightarrow wp(\mathtt{S}, R)$
  - Assume: $Q \land P$, which implies $\boxed{Q}$
  - According to **(A1)**, we have $wp(\mathtt{S}, R)$. ∎

Proof Tips (2)

When calculating $wp(\mathtt{S}, R)$, if either program $\mathtt{S}$ or postcondition R involves array indexing, then R should be augmented accordingly.

e.g., Before calculating $wp(\mathtt{S}, a[i] > 0)$, augment it as

$$wp(\mathtt{S}, a.lower \leq i \leq a.upper \land a[i] > 0)$$

e.g., Before calculating $wp(\mathtt{x\ :=\ a[i]}, R)$, augment it as

$$wp(\mathtt{x\ :=\ a[i]}, a.lower \leq i \leq a.upper \land R)$$

Beyond this lecture

Exercise on proving the *total correctness* of a program:

https://www.eecs.yorku.ca/~jackie/teaching/lectures/2020/F/EECS3311/exercises/EECS3311_F20_Exercise_WP.sol.pdf

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