301AA - Advanced Programming

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***AP-22**: On Designing Software Frameworks*

Software Framework Design

- Intellectual Challenging Task
- Requires a deep understanding of the application domain
- Requires mastering of **software (design) patterns**, **OO methods** and **polymorphism** in particular
- Impossible to address in the course, but we can play a bit…
  - *Using classic problems to teach Java framework design, by H.C. Cunningham, Yi Liu and C. Zhang,* Science of Computer Programming 59 (2006).

Four levels for understanding frameworks

1. Frameworks are normally implemented in an object-oriented language such as Java ➔ Understanding the applicable language concepts, which include inheritance, polymorphism, encapsulation, and delegation.
2. Understanding the framework concepts and techniques sufficiently well to use frameworks to build a custom application
3. Being able to do detailed design and implementation of frameworks for which the **common** and **variable aspects** are already known.
4. Learning to analyze a potential software family, identifying its possible common and variable aspects, and evaluating alternative framework architectures.

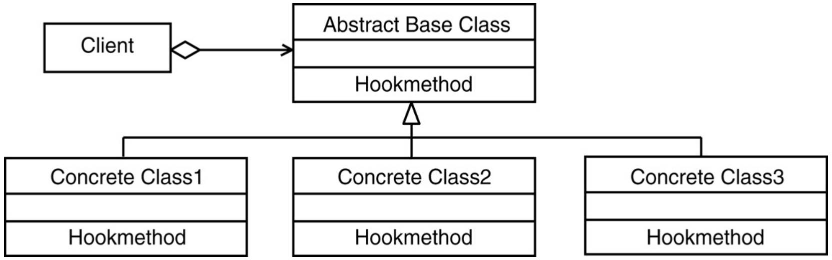
A Framework for the family of **Divide and Conquer** algorithms

- Idea: start from a well-known generic algorithm
- Apply known techniques and patterns to define a framework for a ***software family***
- Instances of the framework, obtained by standard extension mechanism, will be concrete algorithms of the family

```
function solve (Problem p) returns Solution
{ if isSimple(p)
    return simplySolve(p);
  else
sp[] = decompose(p);
for (i= 0; i < sp.length; i = i+1)
    sol[i] = solve(sp[i]);
  return combine(sol);
}
```

Some terminology…

- ***Frozen Spot***: common (shared) aspect of the software family
- ***Hot Spot***: variable aspect of the family
- ***Template method***: concrete method of base (abstract) class implementing behavior common to all members of the family
- A hot spot is represented by a group of abstract ***hook methods***.
- A template method calls a hook method to invoke a function that is specific to one family member [***Inversion of Control***]
- A hot spot is realized in a framework as a ***hot spot subsystem***:
  - An abstract base class + some concrete subclasses

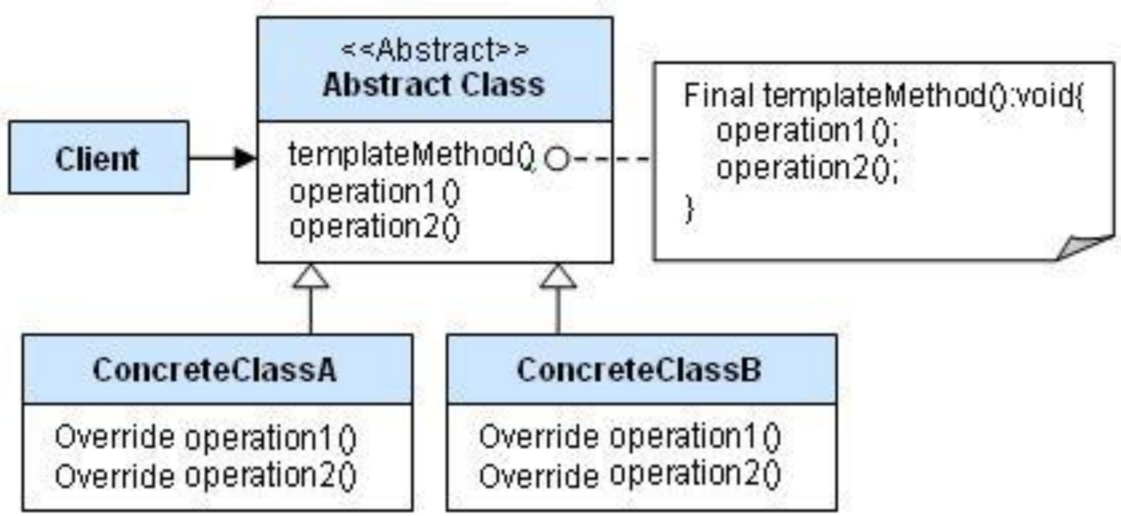


Two Principles for Framework Construction

- The ***unification principle*** [**Template Method** Design Pattern]
  - It uses **inheritance** to implement the **hot spot subsystem**
  - Both the template methods and hook methods are defined in the same abstract base class
  - The hook methods are implemented in subclasses of the base class
- The ***separation principle*** [**Strategy** Design Pattern]
  - It uses **delegation** to implement the **hot spot subsystem**
  - The template methods are implemented in a concrete context class; the hook methods are defined in a separate abstract class and implemented in its subclasses
  - The template methods delegate work to an instance of the subclass that implements the hook methods

The **Template Method** design pattern

- One of the behavioural pattern of the Gang of Four
- **Intent**: Define the skeleton of an algorithm in an operation, deferring some steps to subclasses.
- A **template method** belongs to an abstract class and it defines an algorithm in terms of abstract operations that subclasses override to provide concrete behavior.
- Template methods call, among others, the following operations:
  - **concrete operations** of the abstract class (i.e., fixed parts of the algorithm);
  - **primitive operations**, i.e., abstract operations, that subclasses **have** to implement; and
  - **hook operations**, which provide default behavior that subclasses **may** override if necessary. A hook operation often does nothing by default.



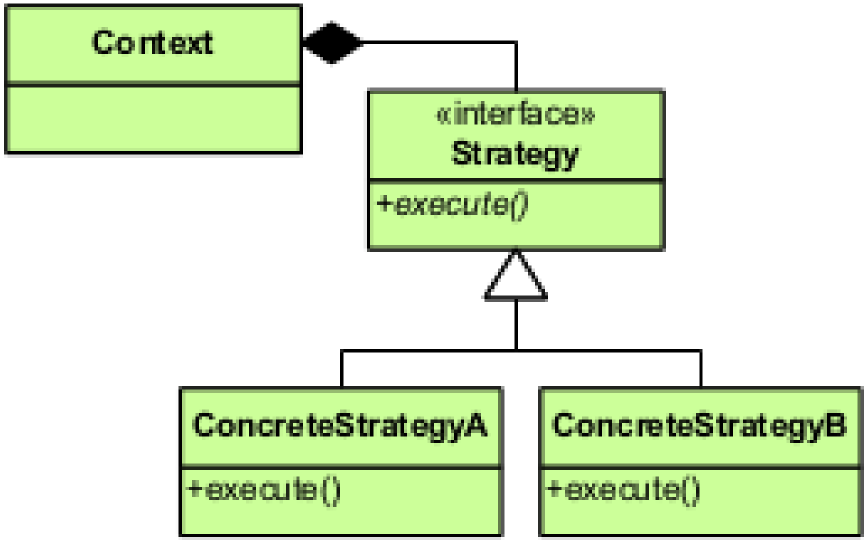
```
Final templateMethod():void{
   operation1();
   operation2();
}
```

Implementation of Template Methods

- Using **Java** visibility modifiers
  - The template method itself should not be overridden: it can be declared a **public final method**
  - The **concrete operations** can be declared **private** ensuring that they are only called by the template method
  - **Primitive operations** that **must** be overridden are declared **protected abstract**
  - The hook operations that **may** be overridden are declared **protected**
- Using **C++** access control
  - The template method itself should not be overridden: it can be declared a **nonvirtual member function**
  - The **concrete operations** can be declared **protected members** ensuring that they are only called by the template method
  - **Primitive operations** that **must** be overridden are declared **pure virtual**
  - The hook operations that **may** be overridden are declared **protected virtual**

The **Strategy** design pattern

- One of the behavioural pattern of the Gang of Four
- **Intent**: Allows to select (part of) an algorithm at runtime
- The client uses an object implementing the interface and invokes methods of the interface for the hot spots of the algorithm



Applying the **unification principle**: UML diagram of the solution

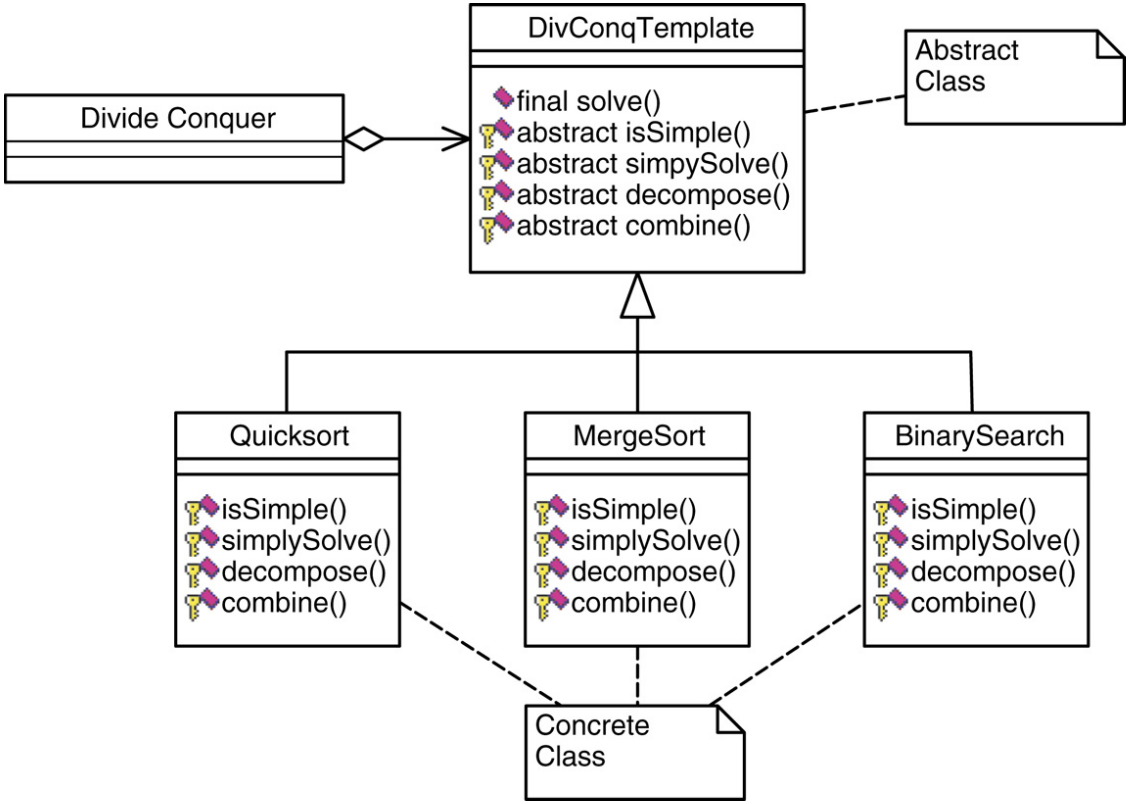


Fig. 3. Template method for divide and conquer.

```
function solve (Problem p) returns Solution  // template method
{ if isSimple(p)                             // hot spots
        return simplySolve(p);
    else
        sp[] = decompose(p);
        for (i= 0; i < sp.length; i = i+1)
            sol[i] = solve(sp[i]);
    return combine(sol);
}
```

Java code of the framework (*unification principle*)

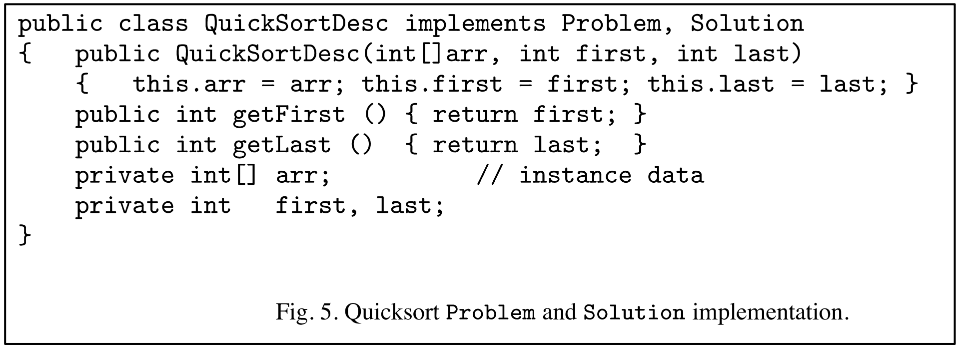
```
public interface Problem {};
public interface Solution {};
```

```
abstract public class DivConqTemplate
{   public final Solution solve(Problem p)
    {   Problem[] pp;
        if (isSimple(p)){ return simplySolve(p); }
        else            { pp = decompose(p); }
        Solution[] ss = new Solution[pp.length];
        for(int i=0; i < pp.length; i++)
        {   ss[i] = solve(pp[i]);   }
        return combine(p,ss);
    }
    abstract protected boolean isSimple (Problem p);
    abstract protected Solution simplySolve (Problem p);
    abstract protected Problem[] decompose (Problem p);
    abstract protected Solution combine(Problem p,Solution[] ss);
}
```

```
function solve (Problem p) returns Solution  // template method
{ if isSimple(p)                             // hot spots
        return simplySolve(p);
    else
        sp[] = decompose(p);
        for (i= 0; i < sp.length; i = i+1)
            sol[i] = solve(sp[i]);
    return combine(sol);
}
```

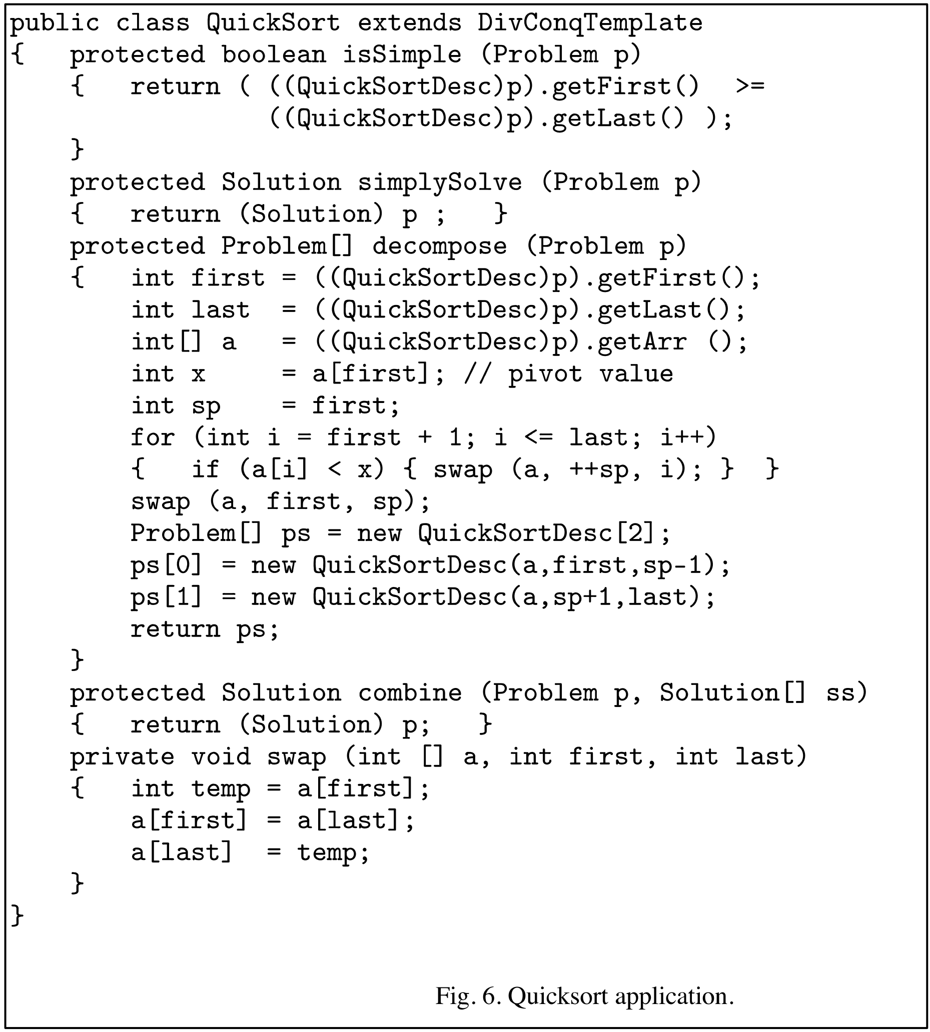
An application of the framework: **QuickSort** (*unification principle*)

- In-place sorting
- Both problem and solution described by the same structure: <array, first, last>



```
public class QuickSortDesc implements Problem, Solution
{   public QuickSortDesc(int[]arr, int first, int last)
    {   this.arr = arr; this.first = first; this.last = last; }
    public int getFirst () { return first; }
    public int getLast ()  { return last;  }
    private int[] arr;          // instance data
    private int   first, last;
}
```

Fig. 5. Quicksort `Problem` and `Solution` implementation.



```
public class QuickSort extends DivConqTemplate
{   protected boolean isSimple (Problem p)
    {   return ( ((QuickSortDesc)p).getFirst()   >=
                 ((QuickSortDesc)p).getLast() );
    }
    protected Solution simplySolve (Problem p)
    {   return (Solution) p ;   }
    protected Problem[] decompose (Problem p)
    {   int first = ((QuickSortDesc)p).getFirst();
        int last  = ((QuickSortDesc)p).getLast();
        int[] a   = ((QuickSortDesc)p).getArr ();
        int x     = a[first]; // pivot value
        int sp    = first;
        for (int i = first + 1; i <= last; i++)
        {   if (a[i] < x) { swap (a, ++sp, i); }  }
        swap (a, first, sp);
        Problem[] ps = new QuickSortDesc[2];
        ps[0] = new QuickSortDesc(a,first,sp-1);
        ps[1] = new QuickSortDesc(a,sp+1,last);
        return ps;
    }
    protected Solution combine (Problem p, Solution[] ss)
    {   return (Solution) p;   }
    private void swap (int [] a, int first, int last)
    {   int temp = a[first];
        a[first] = a[last];
        a[last]  = temp;
    }
}
```

Fig. 6. Quicksort application.

- **Merge-sort** can be defined similarly
- In that case, combine would do most of the work

Applying the **separation principle**: UML diagram of the solution

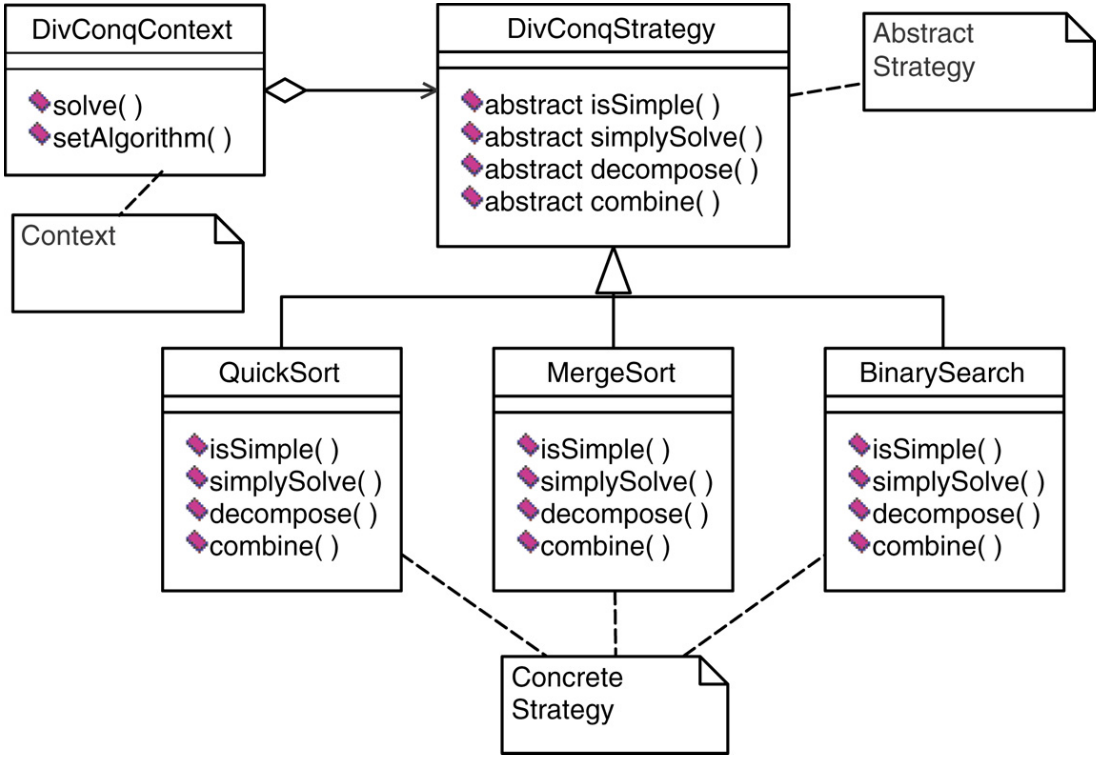


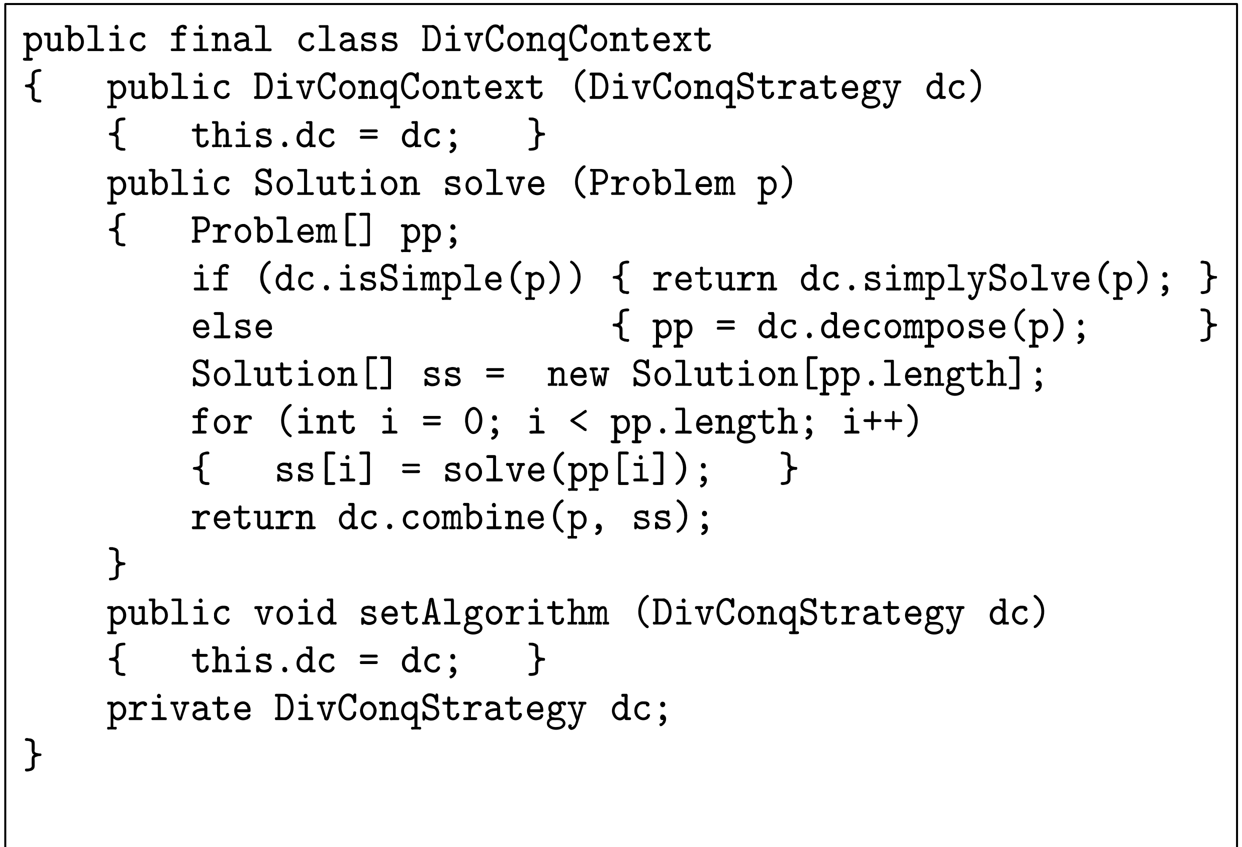
Fig. 7. Strategy pattern for divide and conquer framework.

```
function solve (Problem p) returns Solution  // template method
{ if isSimple(p)                             // hot spots
        return simplySolve(p);
    else
        sp[] = decompose(p);
        for (i= 0; i < sp.length; i = i+1)
            sol[i] = solve(sp[i]);
    return combine(sol);
}
```

Code of the framework (*separation principle*)

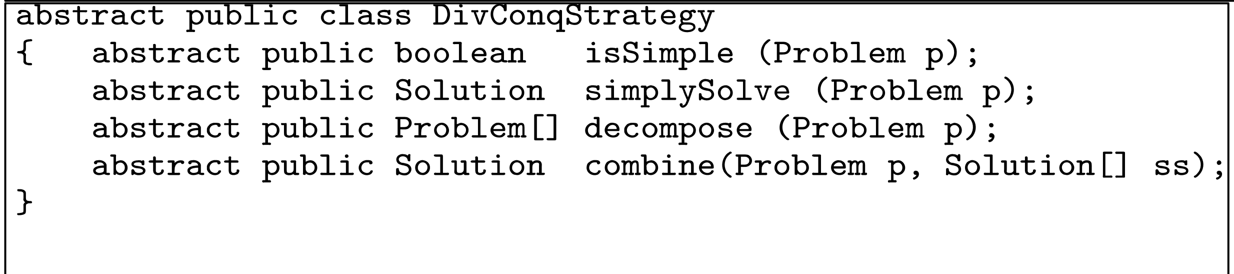
The client delegates the hot spots to an object implementing the strategy

The implementations of DivConqStrategy are similar to the previous case



```
public final class DivConqContext
{   public DivConqContext (DivConqStrategy dc)
    {   this.dc = dc;   }
    public Solution solve (Problem p)
    {   Problem[] pp;
        if (dc.isSimple(p)) { return dc.simplySolve(p); }
        else                { pp = dc.decompose(p);     }
        Solution[] ss =  new Solution[pp.length];
        for (int i = 0; i < pp.length; i++)
        {   ss[i] = solve(pp[i]);   }
        return dc.combine(p, ss);
    }
    public void setAlgorithm (DivConqStrategy dc)
    {   this.dc = dc;   }
    private DivConqStrategy dc;
}
```

Fig. 8. Strategy context class implementation.



```
abstract public class DivConqStrategy
{   abstract public boolean   isSimple (Problem p);
    abstract public Solution  simplySolve (Problem p);
    abstract public Problem[] decompose (Problem p);
    abstract public Solution  combine(Problem p, Solution[] ss);
}
```

Fig. 9. Strategy object abstract class.

Unification vs. separation principle
Template method vs. Strategy DP

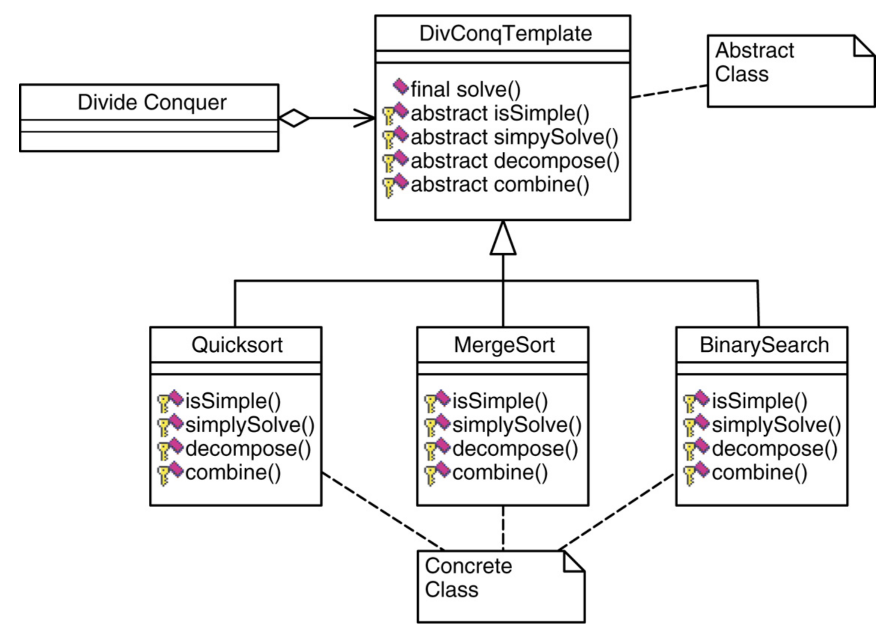


Fig. 3. Template method for divide and conquer.

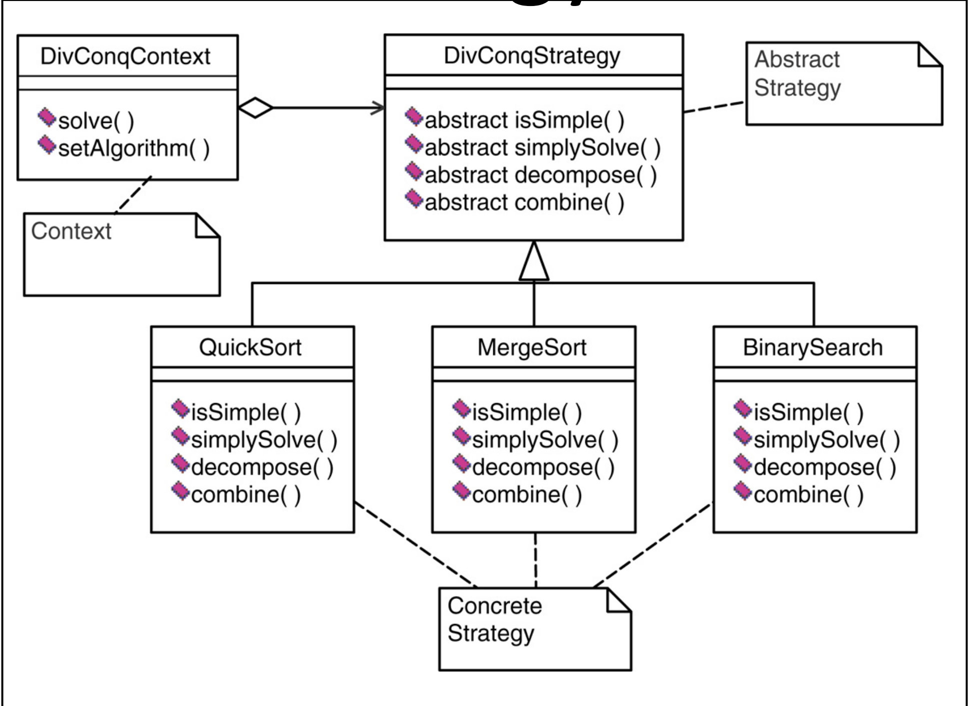


Fig. 7. Strategy pattern for divide and conquer framework.

- The two approaches differ in the coupling between client and chosen algorithm
- With Strategy, the coupling is determined by dependency (setter) injection, and could change at runtime

Framework development by generalization

- We address now level 4 of "framework understanding"
  - *Learning to analyze a potential software family, identifying its possible common and variable aspects, and evaluating alternative framework architectures. Framework design involves incrementally evolving a design rather than discovering it in one single step.*
- This “evolution” consists of
  - examining existing designs for family members
  - identifying the frozen spots and hot spots of the family
  - **generalizing** the program structure to enable
    - reuse of the code for frozen spots and
    - use of different implementations for each hot spot.
- We present an example based on **binary trees traversals**, starting from a **concrete algorithm for printing a tree with preorder traversal**

Binary trees and preorder traversal

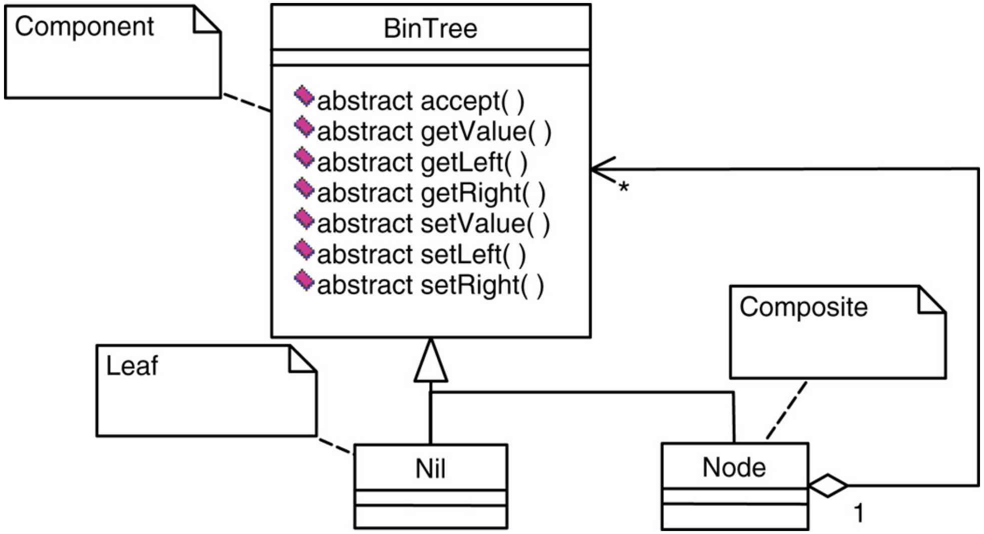


Fig. 10. Binary tree using Composite design pattern.

Binary trees as instance of the **Composite** design pattern

- Provides uniform access to nodes and to leaves

```
procedure preorder(t)
{   if t null, then return;
    perform visit action for root node of tree t;
    preorder(left subtree of t);
    preorder(right subtree of t);
}
```

Pseudo-code of generic **depth-first preorder left-to-right** traversal (**action** not specified)

Binary tree class hierarcy

```
abstract public class BinTree
{   public void setValue(Object v)  { }        // mutators
    public void setLeft(BinTree l)  { }        //  default
    public void setRight(BinTree r) { }
    abstract public void preorder();           // traversal
    public Object  getValue() { return null; } // accessors
    public BinTree getLeft()  { return null; } //   default
    public BinTree getRight() { return null; }
}
```

Abstract class defining defaults and abstract methods

```
public class Node extends BinTree
{   public Node(Object v, BinTree l, BinTree r)
    {   value = v; left = l; right = r; }
    public void setValue(Object v)  { value = v; }  // mutators
    public void setLeft(BinTree l)  { left = l;  }
    public void setRight(BinTree r) { right = r; }
    public void preorder()                          // traversal
    {   System.out.println("Visit node with value:  " + value);
        left.preorder(); right.preorder();
    }
    public Object  getValue() { return value; }     // accessors
    public BinTree getLeft()  { return left;  }
    public BinTree getRight() { return right; }
    private Object  value;                          // instance data
    private BinTree left, right;
}
```

Implementation of the abstract class for Nodes

- The **action** simply prints

```
public class Nil extends BinTree
{   private Nil() { }   // private to require use of getNil()
    public void preorder() { };                       // traversal
    static public BinTree getNil() { return theNil; } // Singleton
    static public BinTree theNil = new Nil();
}
```

Implementation of the abstract class for leaves, using the **Singleton DP**

Identifying Frozen and Hot Spots

Possible choices, generalizing the concrete program to a family of tree-traversal algorithms

- **Frozen Spots** (fixed for the whole family)
  - The structure of the tree, as defined by the BinTree hierarchy
  - A traversal accesses every element of the tree once, but it can stop before completing
  - A traversal performs one or more visit actions accessing an element of the tree

Identifying Frozen and Hot Spots

- **Hot Spots** (to be fixed in each element of the family)
  1. Variability in the visit operation's action: a function of the current node's value and the accumulated result
  2. Variability in ordering of the visit action with respect to subtree traversals. Should support preorder, postorder, in-order, and their combination
  3. Variability in the tree navigation technique. Should support any access order (not only left-to-right, depth-first, total traversals)

Hot Spot #1: Generalizing the visit action

- Using the *separation principle* (**Strategy** pattern) we allow different visit actions on the same tree
- action is represented by the abstract method **visitPre**
- It takes an accumulator Object and a BinTree as arguments

```
public interface PreorderStrategy
{   abstract public Object visitPre(Object ts, BinTree t); }
```

```
abstract public class BinTree
{   ...
    abstract public Object preorder(Object ts, PreorderStrategy v);
    ...
}
```

```
public class Node extends BinTree
{   ...
    public Object preorder(Object ts,PreorderStrategy v) //traversal
    {   ts = v.visitPre(ts, this);
        ts = left.preorder(ts, v);
        ts = right.preorder(ts, v);
        return ts;
    }
    ...
}
```

```
public class Nil extends BinTree
{   ...
    public Object preorder(Object ts, PreorderStrategy v)
    {   return ts; }
    ...
}
```

New BinTree hierarcy.

The preorder method takes the action from the strategy and handles accumulation

Exercise: define strategies for printing the values of the nodes, and for computing the sum / max of all node values

Hot Spot #2: Generalizing the visit order

We generalize the previous hot spot subsystem

- The **Euler Strategy** visits each node three times (*left* = pre, *right* = post, *bottom* = in)

```
public interface EulerStrategy
{   abstract public Object visitLeft(Object ts, BinTree t);
    abstract public Object visitBottom(Object ts, BinTree t);
    abstract public Object visitRight(Object ts, BinTree t);
    abstract public Object visitNil(Object ts, BinTree t);
}
```

```
abstract public class BinTree
{   ...
    abstract public Object traverse(Object ts, EulerStrategy v);
    ...
}
```

preorder is now **traverse**

```
public class Node extends BinTree
{   ...
    public Object traverse(Object ts, EulerStrategy v) // traversal
    {   ts = v.visitLeft(ts,this);     // upon arrival from above
        ts = left.traverse(ts,v);
        ts = v.visitBottom(ts,this);   // upon return from left
        ts = right.traverse(ts,v);
        ts = v.visitRight(ts,this);    // upon completion
        return ts;
    }
    ...
}
```

Using the new abstract methods an Euler Strategy can implement any combination of pre-order, post-order or in-order traversal

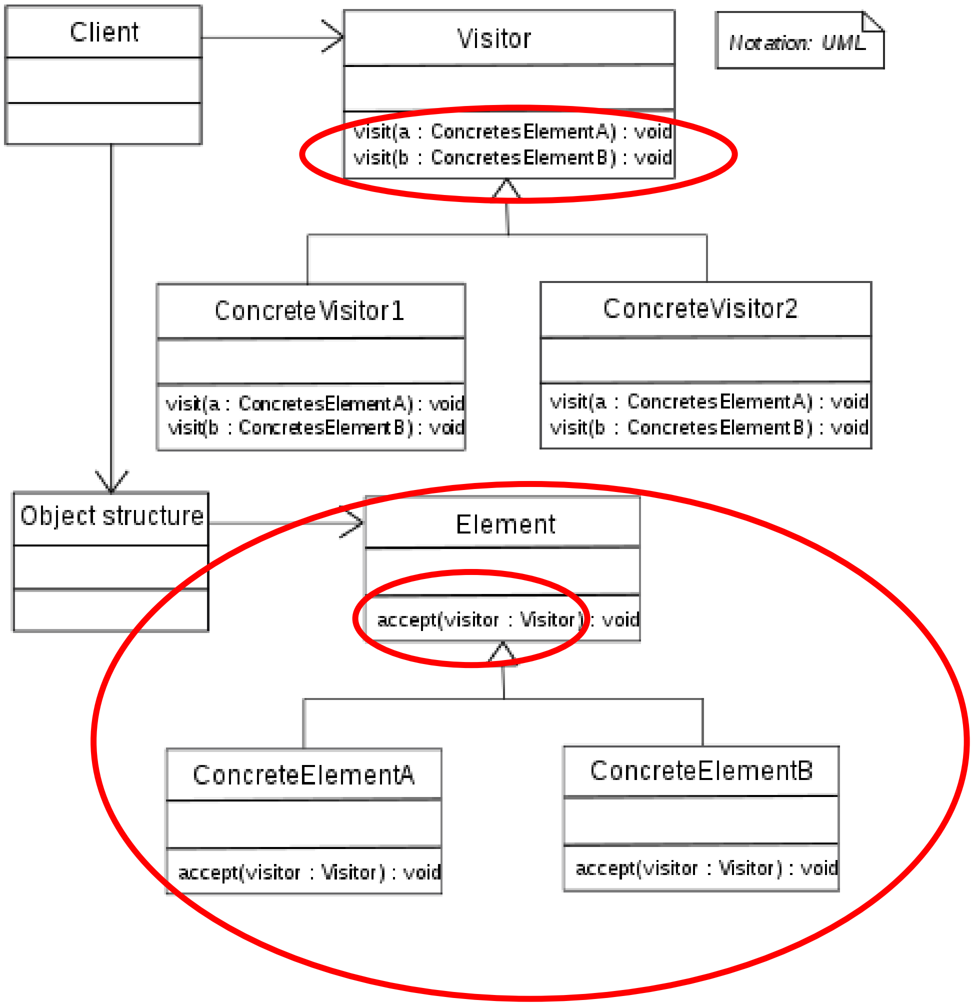
```
public class Nil extends BinTree
{   ...
    public Object traverse(Object ts, EulerStrategy v)
    {   return v.visitNil(ts,this); }
    ...
}
```

Also **visitNil** method added, for the sake of generality

Hot Spot #3: Generalizing the tree navigation

- Support for breadth-first, depth-first, left-to-right, right-to-left, partial traversal, …
- Remember the frozen spots:
  - The structure of the tree, as defined by the BinTree hierarchy: it cannot be modified
  - A traversal accesses every element of the tree once, but it can stop before completing
- Instead of generalizing the **traverse** method, we use the **Visitor** design pattern
- **Visitor** guarantees separation between algorithm and data structure

The **Visitor** design pattern



- The data structure can be made of different types of components (ConcreteElements)
- Each component implements an **accept(Visitor)** method
- The Visitor defines one **visit** method for each type
- The navigation logic is in the Visitor
- At each step, the correct **visit** method is selected by **overloading**

Hot Spot #3: Binary Tree Visitor framework

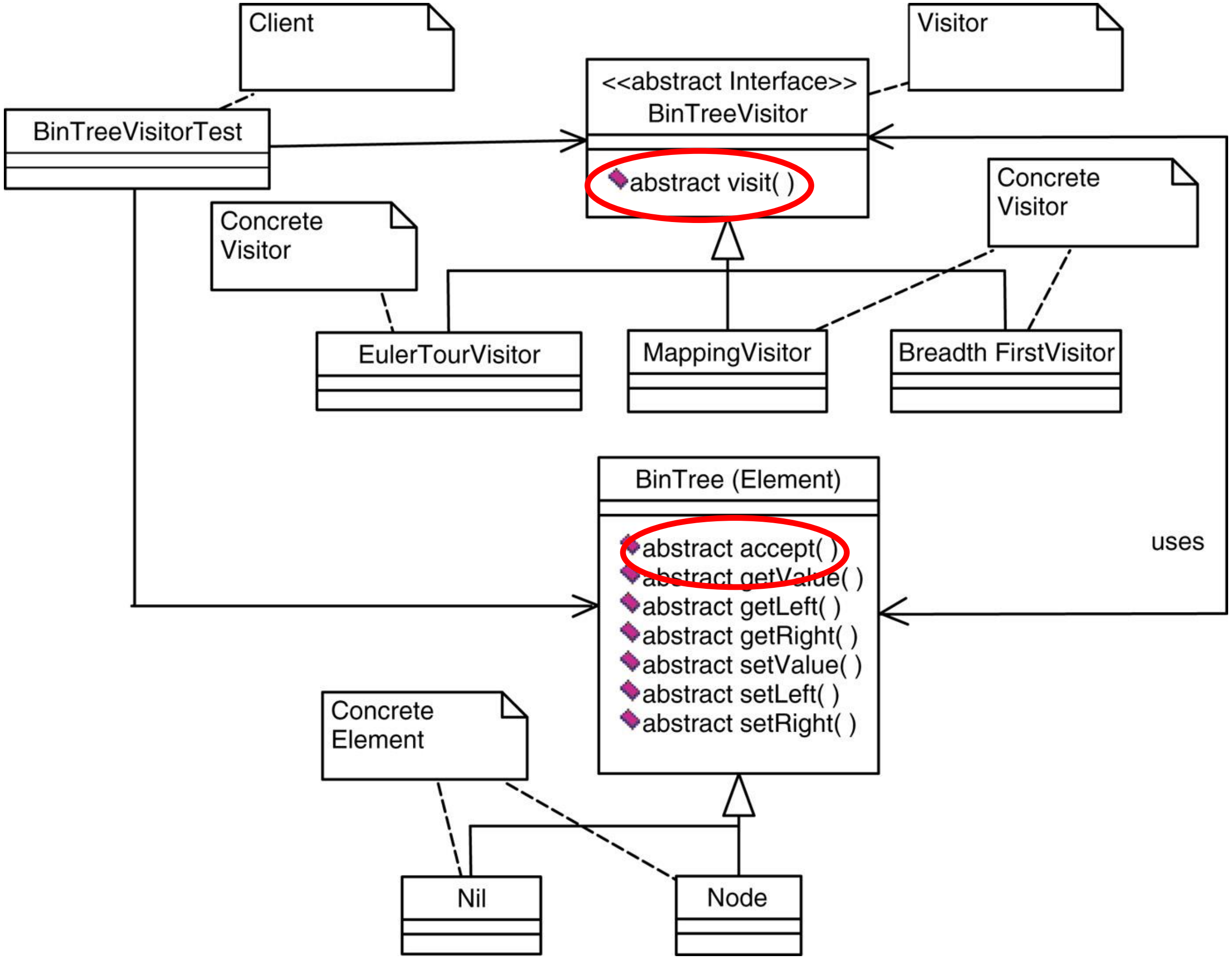


Fig. 14. Binary tree Visitor framework.

Binary Tree Visitor framework: the BinTree code

```
public interface BinTreeVisitor
{   abstract void visit(Node t);
    abstract void visit(Nil t);
}
```

```
abstract public class BinTree
{   public void setValue(Object v)  { }        // mutators
    public void setLeft(BinTree l)  { }        //  default
    public void setRight(BinTree r) { }
    abstract public void accept(BinTreeVisitor v); // accept Visitor
    public Object  getValue() { return null; } // accessors
    public BinTree getLeft()  { return null; } //   default
    public BinTree getRight() { return null; }
}
```

```
public class Node extends BinTree
{   public Node(Object v, BinTree l, BinTree r)
    {   value = v; left = l; right = r; }
    public void setValue(Object v)  { value = v; }  // mutators
    public void setLeft(BinTree l)  { left = l;  }
    public void setRight(BinTree r) { right = r; }
    // accept a Visitor object
    public void accept(BinTreeVisitor v) { v.visit(this); }
    public Object  getValue() { return value; }    // accessors
    public BinTree getLeft()  { return left;  }
    public BinTree getRight() { return right; }
    private Object  value;    // instance data
    private BinTree left, right;
}
```

```
public class Nil extends BinTree
{   private Nil() { }   // private to require use of getNil()
    // accept a Visitor object
    public void accept(BinTreeVisitor v) { v.visit(this); }
    static public BinTree getNil() { return theNil; } // Singleton
    static public BinTree theNil = new Nil();
}
```

The BinTree code is almost unchanged, only the **traverse** method is changed to

- **accept** an instance of Visitor
- invoke **visit(this)** on it

Binary Tree Visitor framework: defining a visitor for Euler Traversal

- The Visitor framework has two levels
  - the Visitor pattern as described above
  - Possibly a second framework for the design of the Visitor objects.
- To implement an Euler tour traversal we
  - design a concrete class EulerTourVisitor that implements the BinTreeVisitor interface
  - this class delegates the specific visit actions to a Strategy object of type EulerStrategy.

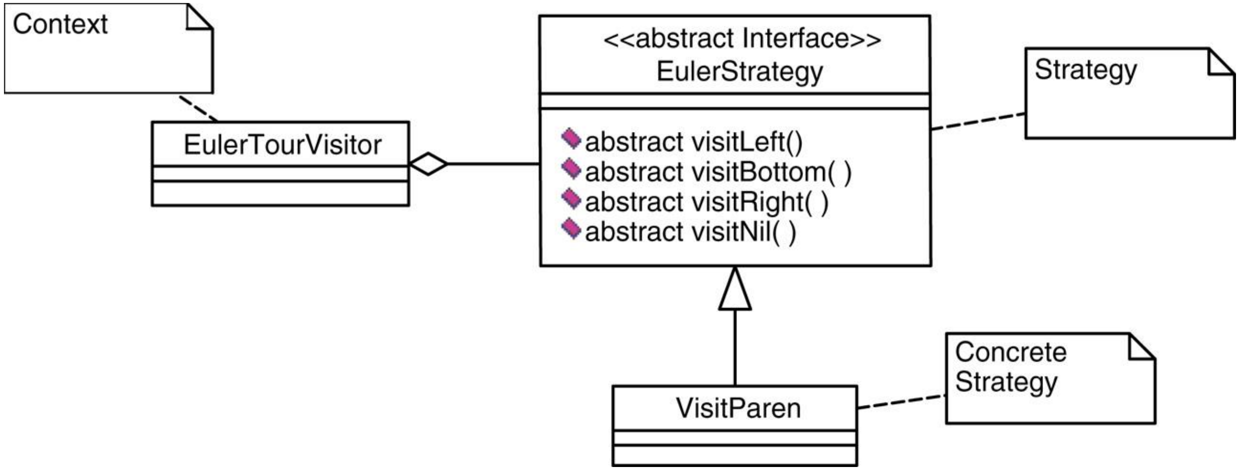


Fig. 16. Euler tour traversal Visitor framework.

Visitor for Euler Traversal using Strategy

```
public interface EulerStrategy
{   abstract public Object visitLeft(Object ts, BinTree t);
    abstract public Object visitBottom(Object ts, BinTree t);
    abstract public Object visitRight(Object ts, BinTree t);
    abstract public Object visitNil(Object ts, BinTree t);
}
```

```
public class EulerTourVisitor implements BinTreeVisitor
{   public EulerTourVisitor(EulerStrategy es, Object ts)
    {   this.es = es;  this.ts = ts; }
    public void setVisitStrategy(EulerStrategy es) // mutators
    {   this.es = es; }
    public void setResult(Object r) { ts = r; }
    public void visit(Node t)       // Visitor hookimplementations
    {   ts = es.visitLeft(ts,t);    // upon first arrival from above
        t.getLeft().accept(this);
        ts = es.visitBottom(ts,t);  // upon return from left
        t.getRight().accept(this);
        ts = es.visitRight(ts,t);   // upon completion of this node
    }
    public void visit(Nil t) { ts = es.visitNil(ts,t); }
    public Object getResult(){ return ts; }  // accessor
    private EulerStrategy es;  // encapsulates state changing ops
    private Object ts;         // traversal state
}
```

- The navigation logic is in the **visit()** method
- It exploits **accept()** to pass to the next node
- The concrete actions are defined in an object implementing **EulerStrategy**
- The strategy is injected with the constructor and can be changed dynamically.

Comparing tree traversal with and without visitor object

```
public class Node extends BinTree
{   ...
    public Object traverse(Object ts, EulerStrategy v) // traversal
    {   ts = v.visitLeft(ts,this);     // upon arrival from above
        ts = left.traverse(ts,v);
        ts = v.visitBottom(ts,this);   // upon return from left
        ts = right.traverse(ts,v);
        ts = v.visitRight(ts,this);    // upon completion
        return ts;
    }
    ...
}
```

Depth-first, left-to-right traversal starts with

root.traverse(acc, es)

```
public class EulerTourVisitor implements BinTreeVisitor
{   public EulerTourVisitor(EulerStrategy es, Object ts)
    {   this.es = es;  this.ts = ts; }
    public void setVisitStrategy(EulerStrategy es) // mutators
    {   this.es = es; }
    public void setResult(Object r) { ts = r; }
    public void visit(Node t)       // Visitor hookimplementations
    {   ts = es.visitLeft(ts,t);    // upon first arrival from above
        t.getLeft().accept(this);
        ts = es.visitBottom(ts,t);  // upon return from left
        t.getRight().accept(this);
        ts = es.visitRight(ts,t);   // upon completion of this node
    }
    public void visit(Nil t) { ts = es.visitNil(ts,t); }
    public Object getResult(){ return ts; }  // accessor
    private EulerStrategy es;  // encapsulates state changing ops
    private Object ts;         // traversal state
}
```

Traversal starts with

root.accept(eulerTVisitor) -> **eulerTourVisitor.visit(root)**

Conclusions

- Software Framework design is a complex task
- Starting point: families of homogeneous software applications
- Identification of frozen spots and hot spots
- Use of design patterns and of other techniques for greater generality and for reducing coupling
- Inversion of control and in particular dependency injection arise naturally
- Suggested reading: ***Why do I hate Frameworks?*** *By Joel Spolsky, co-founder of Stack Overflow*