

301AA - Advanced Programming

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AP-10: 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

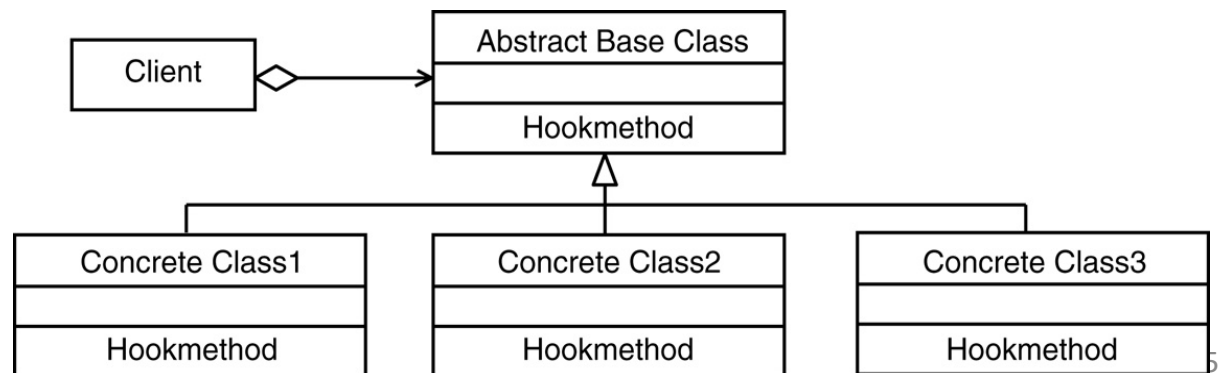
```
function solve (Problem p) returns Solution
{ if isSimple(p)
    return simplySolve(p);
  else
    sp[] = decompose(p);
    for (i= 0; i < sp.length; i = i+1)
      sol[i] = solve(sp[i]);
    return combine(sol);
}
```

- 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

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 **hot spot subsystem**:

- Abstract base class + some concrete subclasses

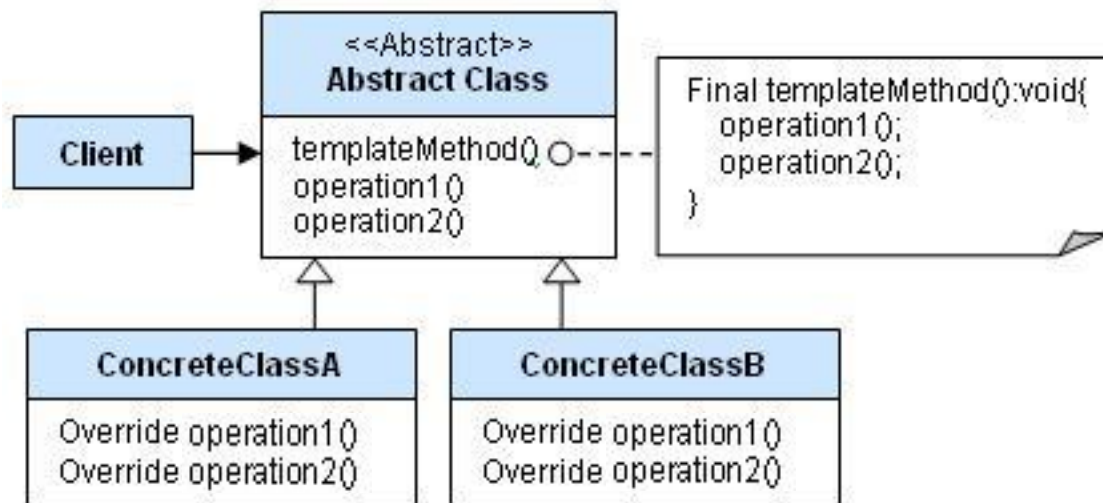


Two Principles for Framework Construction

- The ***unification principle*** [**Template Method** DP]
 - It uses **inheritance** to implement the **hot spot subsystem**
 - Both the **template methods** and **hook methods** are defined in the same abstract base class
 - 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.



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**

Applying the
unification
principle:
UML diagram
of the solution

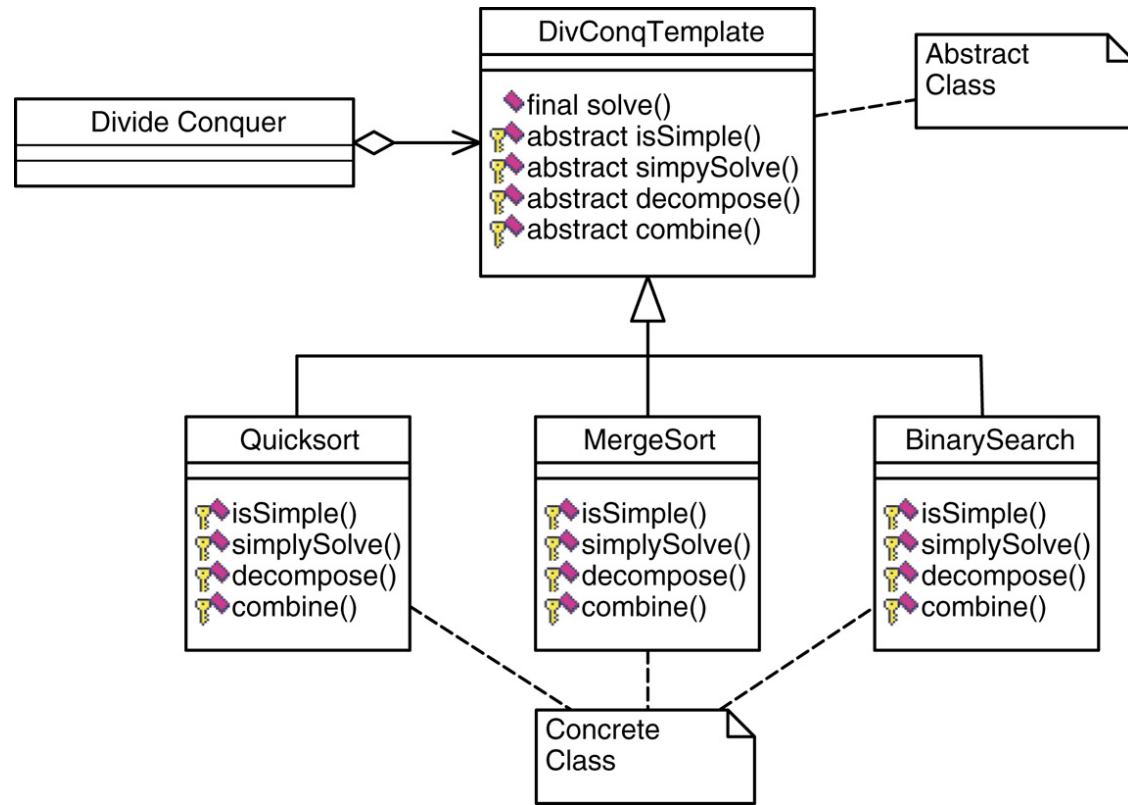


Fig. 3. Template method for divide and conquer.

```
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.

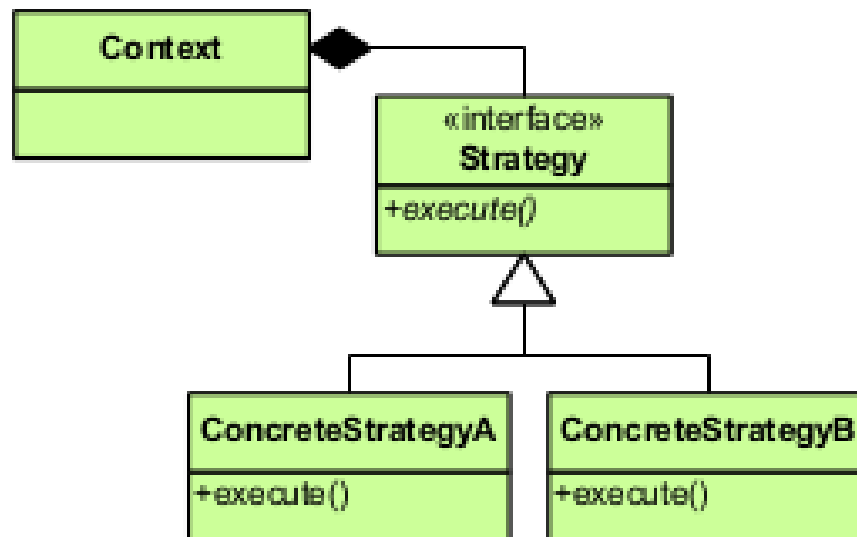
```
public class QuickSort extends DivConqTemplate
{
    protected boolean isSimple (Problem p)
    {
        return ( ((QuickSortDesc)p).getFirst() >=
                ((QuickSortDesc)p).getLast() );
    }
    protected Solution simplySolve (Problem p)
    {
        return (Solution) p; }
    protected 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

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
separation
principle:
UML diagram
of the solution

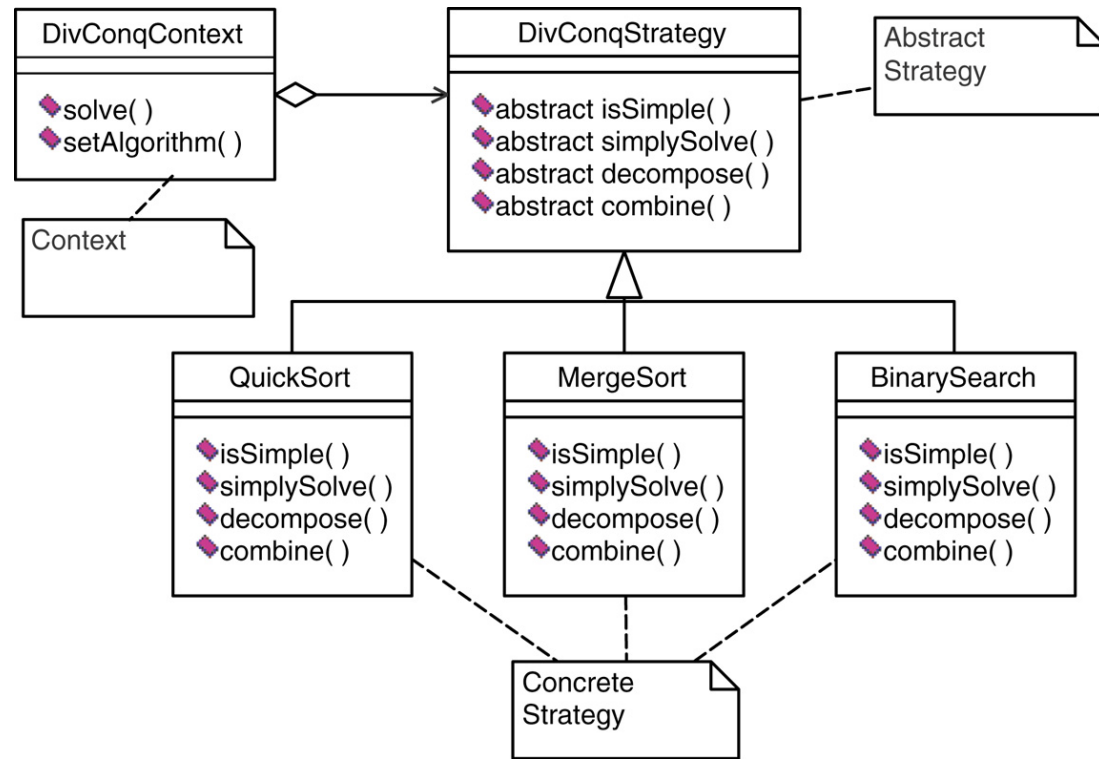


Fig. 7. Strategy pattern for divide and conquer framework.

```
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

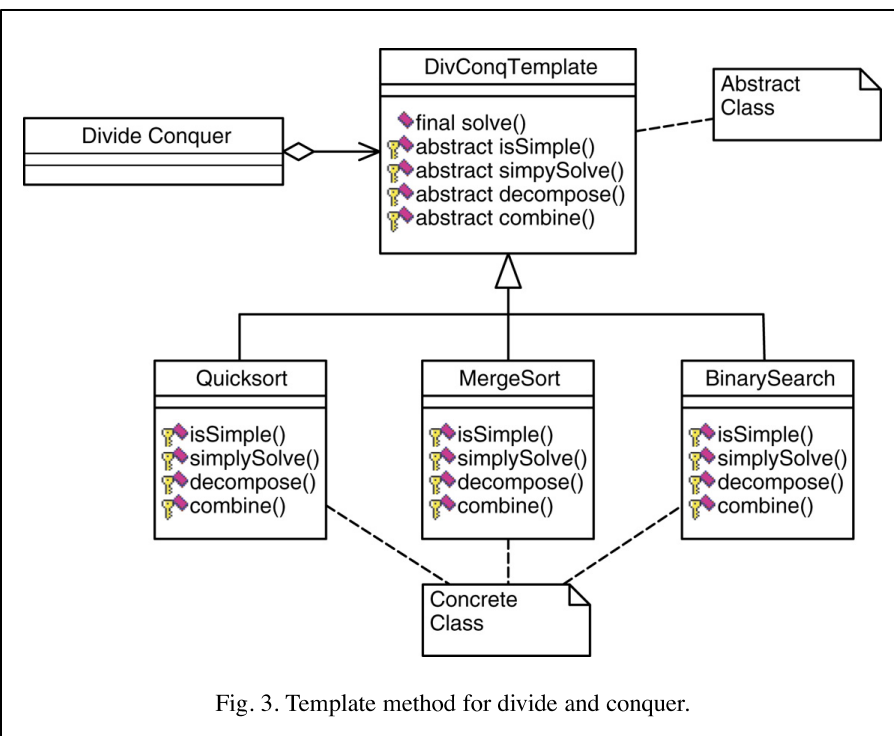


Fig. 3. Template method for divide and conquer.

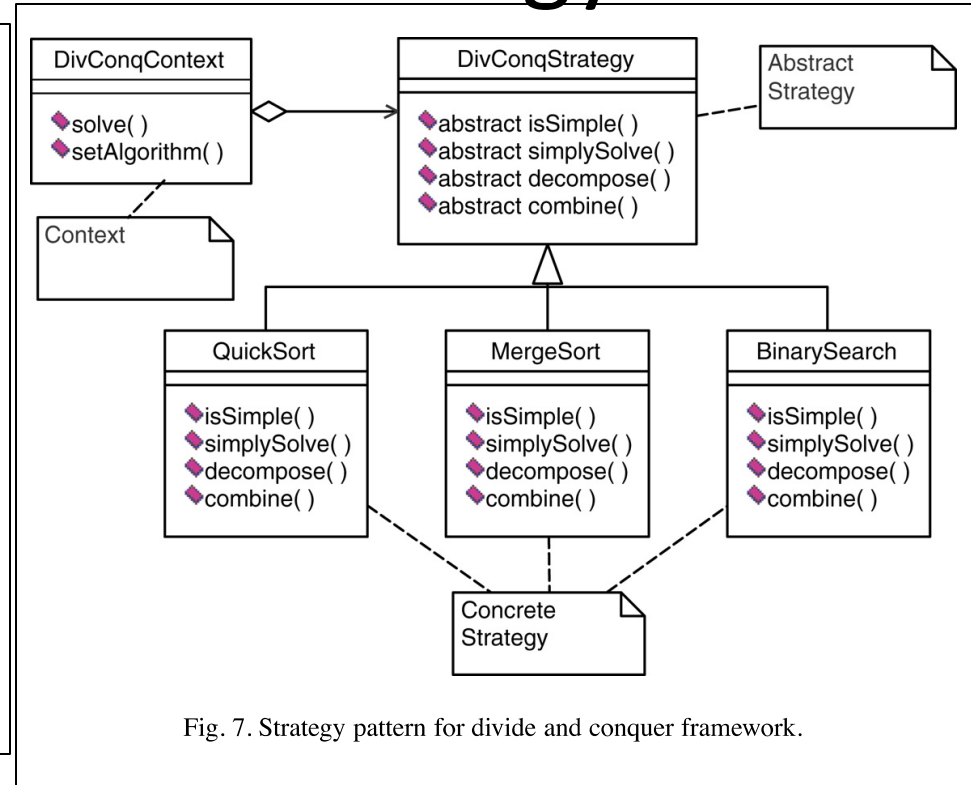


Fig. 7. Strategy pattern for divide and conquer framework.

- 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

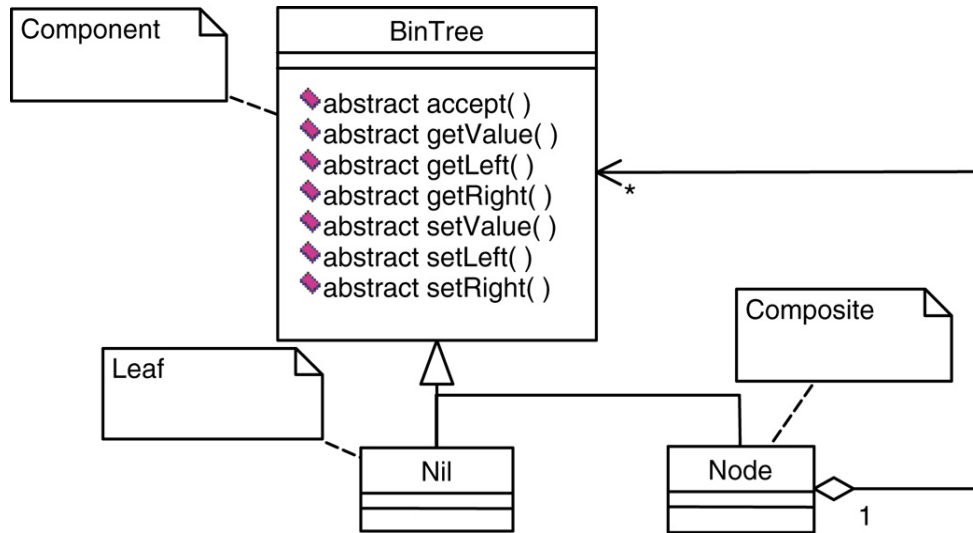


Fig. 10. Binary tree using Composite design pattern.

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 hierarchy

```
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; }
}

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;
}

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();
}
```

Abstract class defining defaults and abstract methods

Implementation of the abstract class for Nodes

- The **action** simply prints

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 hierarchy.

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

```
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);
    ...
}
```

```
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;
    }
    ...
}
```

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

We generalize the previous hot spot subsystem

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

preorder is now **traverse**

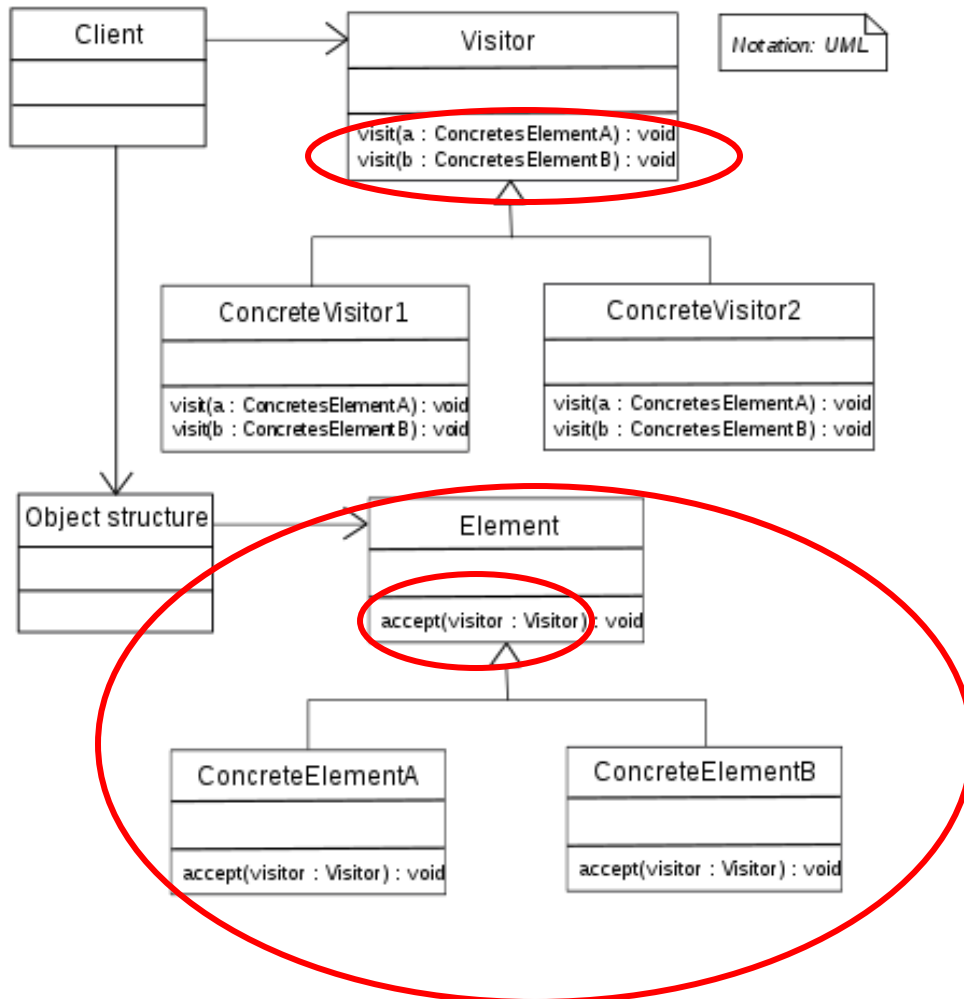
Using the new abstract methods an Euler Strategy can implement any combination of pre-order, post-order or in-order traversal

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

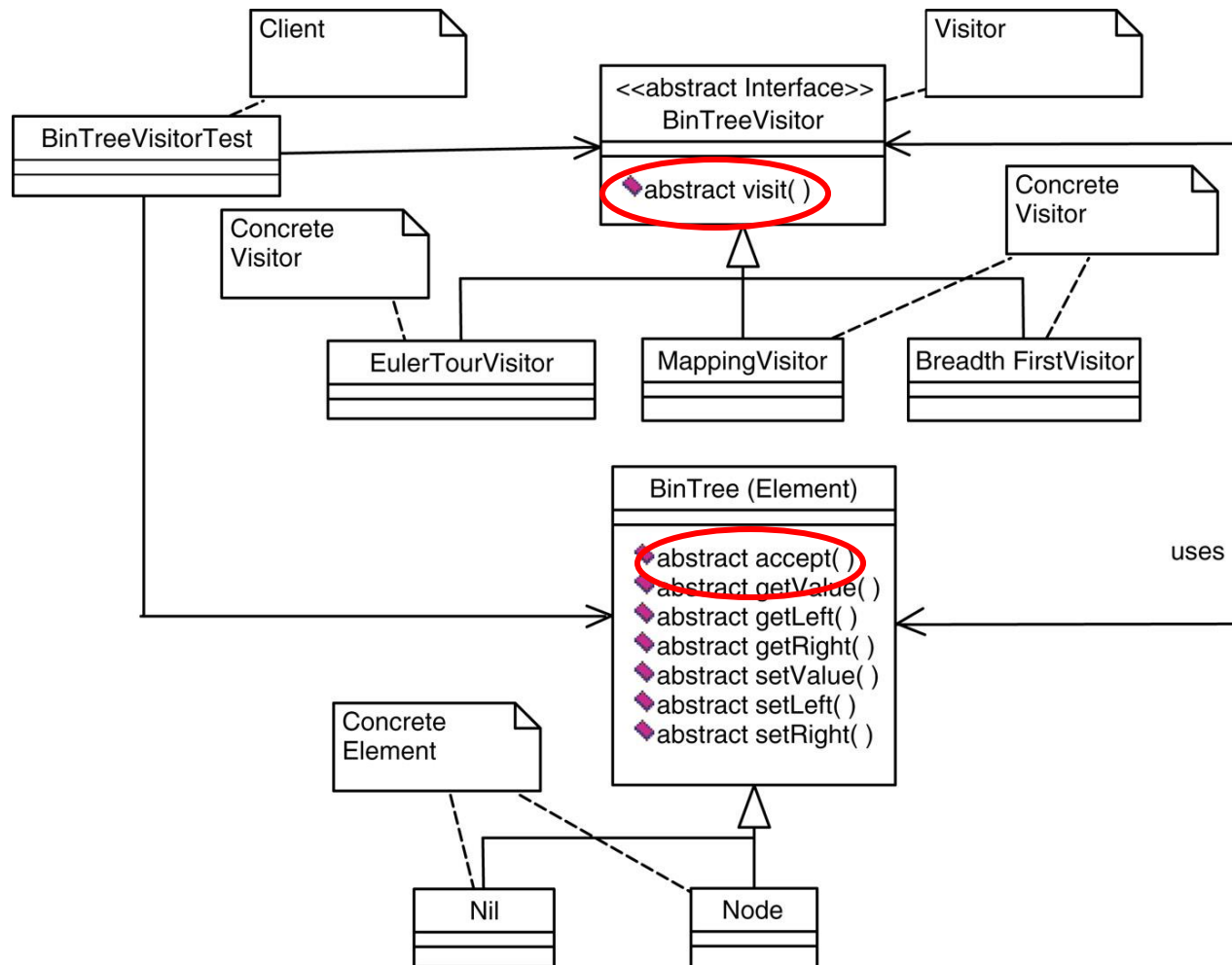


Fig. 14. Binary tree Visitor framework.

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**.

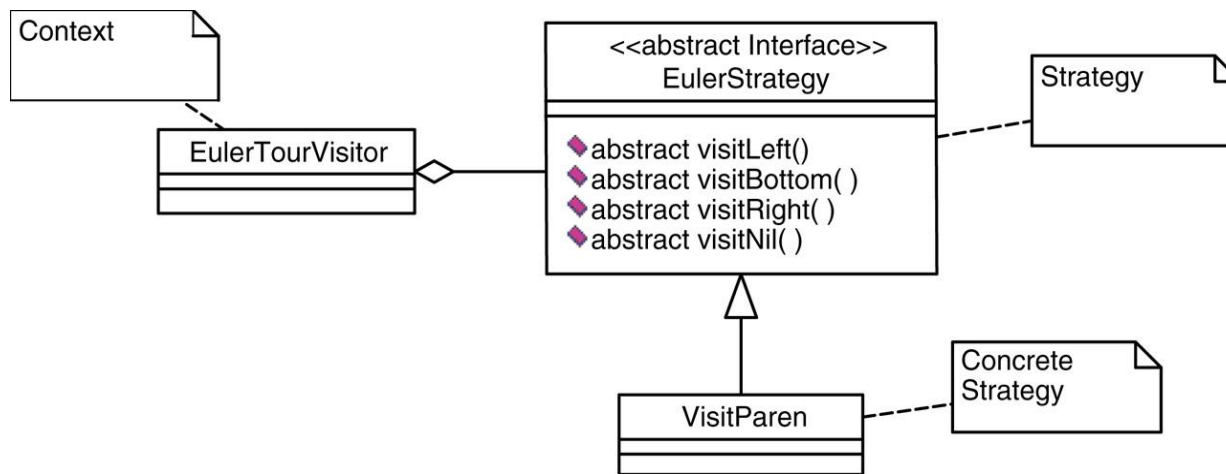


Fig. 16. Euler tour traversal Visitor framework.

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(Null 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