Object-Oriented Design Case Studies with Patterns & C++

Douglas C. Schmidt

Professor
d.schmidt@vanderbilt.edu
www.dre.vanderbilt.edu/~schmidt/

Department of EECS
Vanderbilt University
(615) 343-8197

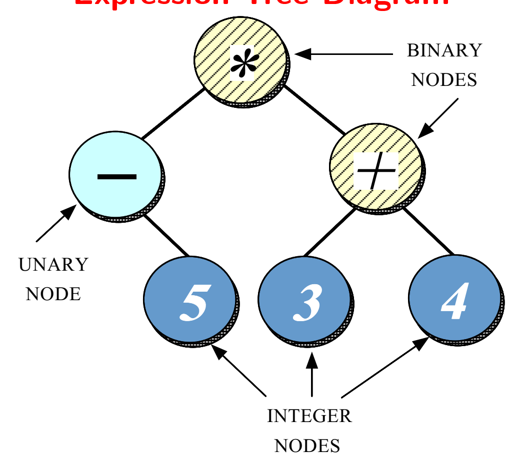
Case Studies Using Patterns

- The following slides describe several case studies using C++ & patterns to build highly extensible software
- The examples include
  1. Expression Tree
     - *e.g.*, Adapter, Factory, Bridge
  2. System Sort
     - *e.g.*, Facade, Adapter, Iterator, Singleton, Factory Method, Strategy, Bridge
  3. Sort Verifier
     - *e.g.*, Strategy, Factory Method, Facade, Iterator, Singleton

Case Study: Expression Tree Evaluator

- The following inheritance & dynamic binding example constructs *expression trees*
  - Expression trees consist of nodes containing operators & operands
    - Operators have different *precedence levels*, different *associativities*, & different *arities*, *e.g.*,
      - Multiplication takes precedence over addition
      - The multiplication operator has two arguments, whereas unary minus operator has only one
    - Operands are integers, doubles, variables, *etc.*
      - We'll just handle integers in this example . . .

Expression Tree Diagram



Expression Tree Behavior

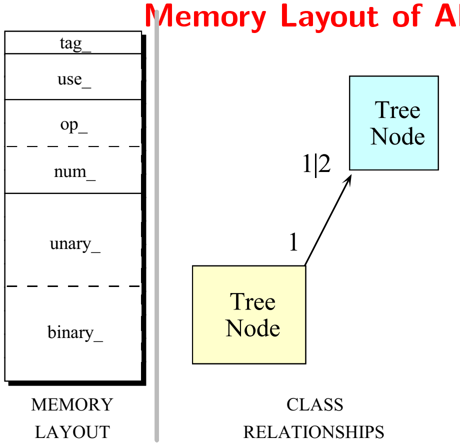
- *Expression trees*
  - Trees may be "evaluated" via different traversals
    - *e.g.*, in-order, post-order, pre-order, level-order
  - The evaluation step may perform various operations, *e.g.*,
    - Traverse & print the expression tree
    - Return the "value" of the expression tree
    - Generate code
    - Perform semantic analysis

Algorithmic Version

- A typical algorithmic method for implementing expression trees involves using a struct/union to represent data structure, *e.g.*,

```
typedef struct Tree_Node Tree_Node;
struct Tree_Node {
  enum { NUM, UNARY, BINARY } tag_;
  short use_; /* reference count */
  union {
    char op_[2];
    int num_;
  } o;
#define num_ o.num_
#define op_ o.op_
  union {
    Tree_Node *unary_;
    struct { Tree_Node *l_, *r_; } binary_;
  } c;
#define unary_ c.unary_
#define binary_ c.binary_
};
```


Memory Layout of Algorithmic Version



- Here's the memory layout of a struct `Tree_Node` object

Print_Tree Function

- A typical algorithmic implementation use a switch statement & a recursive function to build & evaluate a tree, *e.g.*,

```
void print_tree (Tree_Node *root) {
  switch (root->tag_) {
  case NUM: printf ("%d", root->num_);
    break;
  case UNARY:
    printf ("(%s", root->op_[0]);
    print_tree (root->unary_);
    printf (")"); break;
  case BINARY:
    printf ("(");
    print_tree (root->binary_.l_);
    printf ("%s", root->op_[0]);
    print_tree (root->binary_.r_);
    printf (")"); break;
  default:
    printf ("error, unknown type\n");
  }
}
```

Limitations with Algorithmic Approach

- Problems or limitations with the typical algorithmic approach include
  - Little or no use of encapsulation
- Incomplete modeling of the application domain, which results in
  1. Tight coupling between nodes & edges in union representation
  2. Complexity being in *algorithms* rather than the *data structures*
     - *e.g.*, switch statements are used to select between various types of nodes in the expression trees
     - Compare with binary search!
  3. Data structures are "passive" & functions do most processing work explicitly

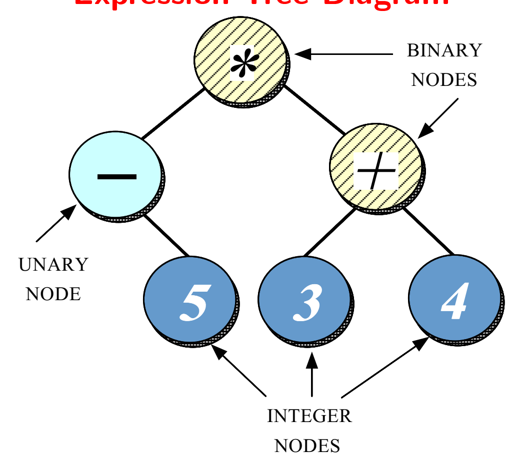
More Limitations with Algorithmic Approach

- The program organization makes it difficult to extend, *e.g.*,
  - Any small changes will ripple through the entire design & implementation
    * *e.g.*, see the "ternary" extension below
  - Easy to make mistakes switching on type tags . . .
- Solution wastes space by making worst-case assumptions *wrt* structs & unions
  - This is not essential, but typically occurs
  - Note that this problem becomes worse the bigger the size of the largest item becomes!

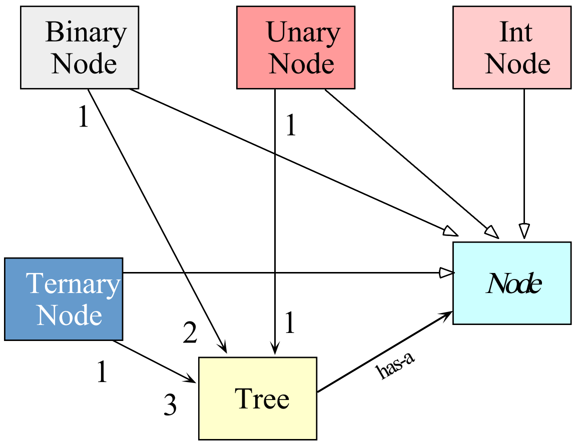
OO Alternative

- Contrast previous algorithmic approach with an object-oriented decomposition for the same problem:
  - Start with OO modeling of the "expression tree" application domain, *e.g.*, go back to original picture
  - Discover several classes involved:
    * class Node: base class that describes expression tree vertices:
      · class Int_Node: used for implicitly converting int to Tree node
      · class Unary_Node: handles unary operators, *e.g.*, -10, +10, !a
      · class Binary_Node: handles binary operators, *e.g.*, a + b, 10 - 30
    * class Tree: "glue" code that describes expression-tree edges, *i.e.*, relations between Nodes
  - Note, these classes model entities in the application domain
    * *i.e.*, nodes & edges (vertices & arcs)

Expression Tree Diagram



Relationships Between Tree & Node Classes



Design Patterns in the Expression Tree Program

- Factory
  - *Centralize the assembly of resources necessary to create an object*
    - *e.g.*, decouple `Node` subclass initialization from use
- Bridge
  - *Decouple an abstraction from its implementation so that the two can vary independently*
    - *e.g.*, printing contents of a subtree and managing memory
- Adapter
  - *Convert the interface of a class into another interface clients expect*
    - *e.g.*, make `Tree` conform C++ iostreams

C++ Node Interface

```
class Tree; // Forward declaration

// Describes the Tree vertices
class Node {
friend class Tree;
protected: // Only visible to derived classes
  Node (): use_ (1) {}

  /* pure */ virtual void print (std::ostream &) const = 0;

  // Important to make destructor virtual!
  virtual ~Node ();
private:
  int use_; // Reference counter.
};
```


C++ Tree Interface

```
#include "Node.h"
// Bridge class that describes the Tree edges and
// acts as a Factory.
class Tree {
public:
  // Factory operations
  Tree (int);
  Tree (const string &, Tree &);
  Tree (const string &, Tree &, Tree &);
  Tree (const Tree &t);
  void operator= (const Tree &t);
  ~Tree ();
  void print (std::ostream &) const;
private:
  Node *node_; // pointer to a rooted subtree
```

C++ Int_Node Interface

```
#include "Node.h"

class Int_Node : public Node {
public:
  Int_Node (int k);
  virtual void print (std::ostream &stream) const;
private:
  int num_; // operand value.
};
```

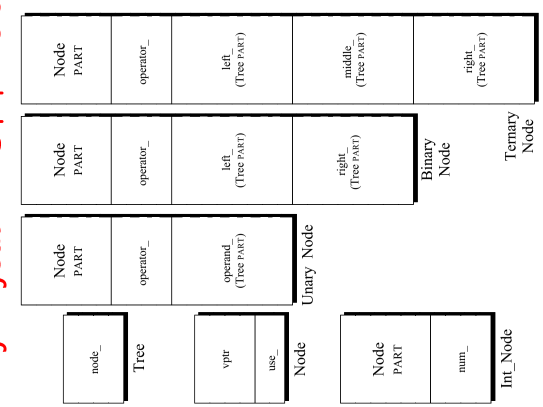

C++ Unary_Node Interface

```
#include "Node.h"

class Unary_Node : public Node {
public:
  Unary_Node (const string &op, const Tree &t);
  virtual void print (std::ostream &stream) const;
private:
  string operation_;
  Tree operand_;
};
```


C++ Binary_Node Interface

```
#include "Node.h"

class Binary_Node : public Node {
public:
  Binary_Node (const string &op,
               const Tree &t1,
               const Tree &t2);
  virtual void print (std::ostream &s) const;
private:
  const string operation_;
  Tree left_;
  Tree right_;
};
```


Memory Layout for C++ Version



- Memory layouts for different subclasses of Node

C++ Int_Node Implementations

```
#include "Int_Node.h"

Int_Node::Int_Node (int k): num_ (k) { }

void Int_Node::print (std::ostream &stream) const {
  stream << this->num_;
}
```


C++ Unary_Node Implementations

```
#include "Unary_Node.h"

Unary_Node::Unary_Node (const string &op, const Tree &t1)
  : operation_ (op), operand_ (t1) { }

void Unary_Node::print (std::ostream &stream) const {
  stream << "(" << this->operation_ <<
         << this->operand_ // recursive call!
         << ")";
}
```


C++ Binary_Node Implementation

```
#include "Binary_Node.h"

Binary_Node::Binary_Node (const string &op,
                          const Tree &t1,
                          const Tree &t2):
  operation_ (op), left_ (t1), right_ (t2) {}

void Binary_Node::print (std::ostream &stream) const {
  stream << "(" << this->left_ // recursive call
         << " " << this->operation_
         << " " << this->right_ // recursive call
         << ")";
}
```

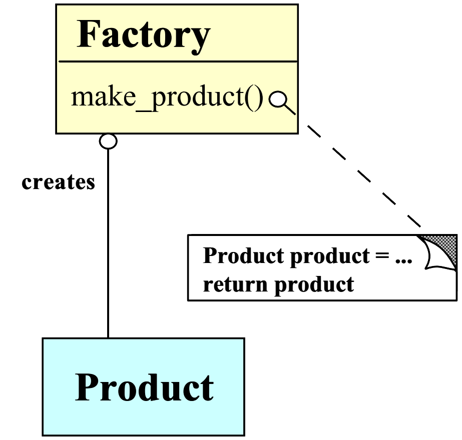

Initializing the Node Subclasses

- *Problem*
  - How to ensure the Node subclasses are initialized properly
- *Forces*
  - There are different types of Node subclasses
    - *e.g.*, take different number & type of arguments
  - We want to centralize initialization in one place because it is likely to change . . .
- *Solution*
  - Use a *Factory* pattern to initialize the Node subclasses

The Factory Pattern

- *Intent*
  - *Centralize the assembly of resources necessary to create an object*
    * Decouple object creation from object use by localizing creation knowledge
- This pattern resolves the following forces:
  - Decouple initialization of the `Node` subclasses from their subsequent use
  - Makes it easier to change or add new Node subclasses later on
    * *e.g.*, Ternary nodes . . .
- A generalization of the GoF Factory Method pattern

Structure of the Factory Pattern



Using the Factory Pattern

- The Factory pattern is used by the Tree class to initialize Node subclasses:

```
 Tree::Tree (int num)
  : node_ (new Int_Node (num)) {}

Tree::Tree (const string &op, const Tree &t)
  : node_ (new Unary_Node (op, t)) {}

Tree::Tree (const string &op,
            const Tree &t1,
            const Tree &t2)
  : node_ (new Binary_Node (op, t1, t2)) {}
```

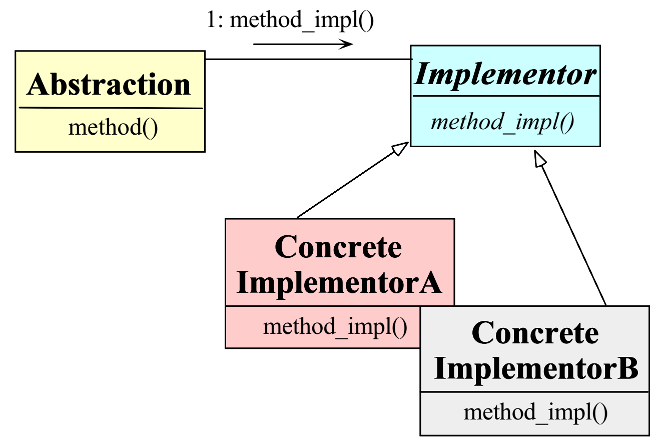

Printing Subtrees

- *Problem*
  - How do we print subtrees without revealing their types?
- *Forces*
  - The `Node` subclass should be hidden within the `Tree` instances
  - We don't want to become dependent on the use of `Node`s, inheritance, & dynamic binding, *etc.*
  - We don't want to expose dynamic memory management details to application developers
- *Solution*
  - Use the *Bridge* pattern to shield the use of inheritance & dynamic binding

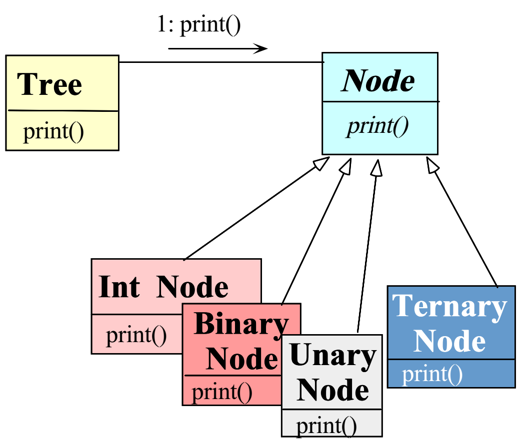
The Bridge Pattern

- *Intent*
  - *Decouple an abstraction from its implementation so that the two can vary independently*
- This pattern resolves the following forces that arise when building extensible software with C++
1. *How to provide a stable, uniform interface that is both closed & open, i.e.,*
   - interface is *closed* to prevent direct code changes
   - Implementation is *open* to allow extensibility
2. *How to manage dynamic memory more transparently & robustly*
3. *How to simplify the implementation of* `operator<<`

Structure of the Bridge Pattern



Using the Bridge Pattern



Illustrating the Bridge Pattern in C++

- The Bridge pattern is used for printing expression trees:

```
void Tree::print (std::ostream &os) const {
  this->node_->print (os);
}
```

- Note how this pattern decouples the `Tree` interface for printing from the `Node` subclass implementation
  - *i.e.*, the `Tree` interface is *fixed*, whereas the `Node` implementation varies
  - However, clients need not be concerned about the variation . . .

Integrating with C++ I/O Streams

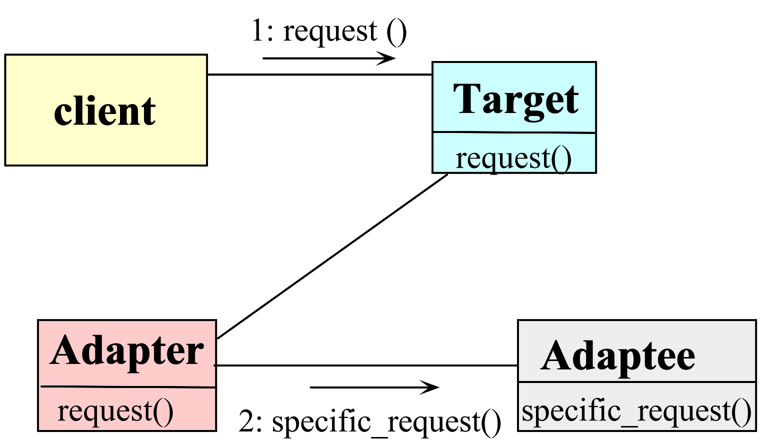
- *Problem*
  - Our `Tree` interface uses a `print` method, but most C++ programmers expect to use I/O Streams
- *Forces*
  - Want to integrate our existing C++ `Tree` class into the I/O Stream paradigm without modifying our class or C++ I/O
- *Solution*
  - Use the *Adapter* pattern to integrate `Tree` with I/O Streams

The Adapter Pattern

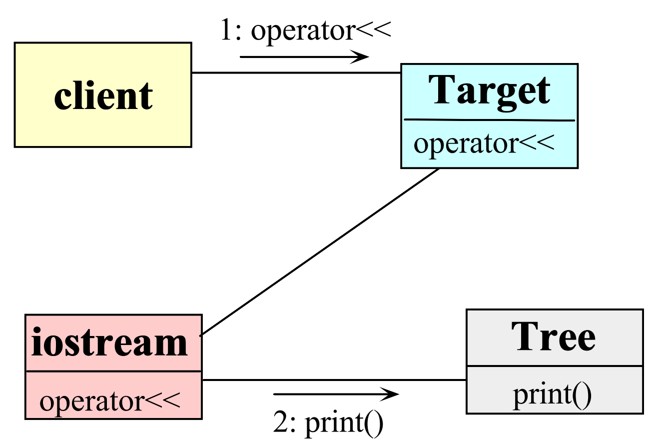
- *Intent*
  - Convert the interface of a class into another interface client expects
    - ∗ Adapter lets classes work together that couldn't otherwise because of incompatible interfaces
- This pattern resolves the following force:

1. How to transparently integrate the `Tree` with the C++ istd::ostream operators

Structure of the Adapter Pattern



Using the Adapter Pattern



Using the Adapter Pattern

- The Adapter pattern is used to integrate with C++ I/O Streams

```
std::ostream &operator<< (std::ostream &s, const Tree &tree) {
  tree.print (s);
  // This triggers Node * virtual call via
  // tree.node_->print (s), which is
  // implemented as the following:
  // (*tree.node_->vptr[1]) (tree.node_, s);
  return s;
}
```

- Note how the C++ code shown above uses I/O streams to "adapt" the `Tree` interface . . .

C++ Tree Implementation

- Reference counting via the "counted body" idiom

```
Tree::Tree (const Tree &t): node_ (t.node_) {
  ++this->node_->use_;   // Sharing, ref-counting.
}

void Tree::operator= (const Tree &t) {
  if (this == &t) return;
 // order important here!
  ++t.node_->use_;
  --this->node_->use_;
  if (this->node_->use_ == 0)
    delete this->node_;
  this->node_ = t.node_;
}
```

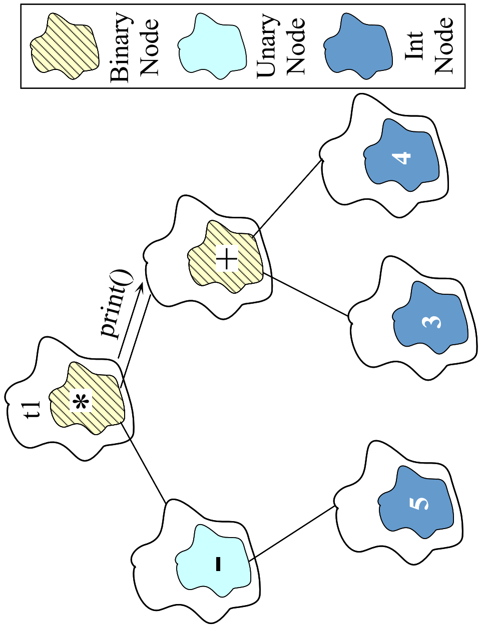

C++ Tree Implementation (cont'd)

```
Tree::~Tree () {
 // Ref-counting, garbage collection
 --this->node_->use_;
 if (this->node_->use_<= 0)
   delete this->node_;
}
```


C++ Main Program

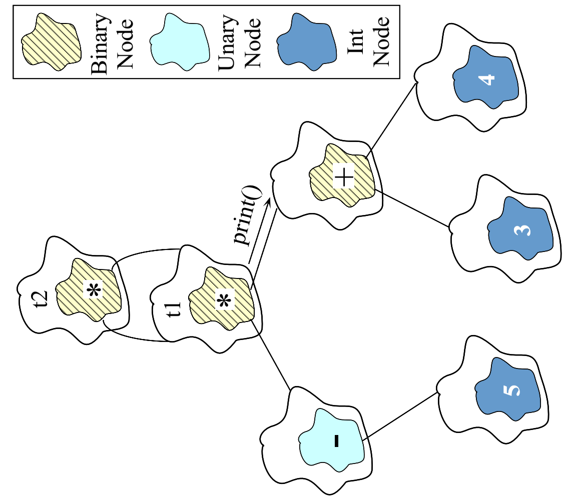
```
#include <istd::ostream.h>
#include "Tree.h"

int main (int, char *[]) {
  const Tree t1 = Tree ("*", Tree ("-", 5),
                        Tree ("+", 3, 4));
  cout << t1 << endl;  // prints ((-5) * (3 + 4))
  const Tree t2 = Tree ("*", t1, t1);

  // prints  (((-5) * (3 + 4)) * ((-5) * (3 + 4))).
  cout << t2 << endl;

  return 0;
  // Destructors of t1 \& t2 recursively
} // delete entire tree when leaving scope.
```

Expression Tree Diagram 1



- Expression tree for t1 = ((-5) * (3 + 4))

Expression Tree Diagram 2



- Expression tree for t2 = (t1 * t1)

Adding Ternary_Nodes

- Extending the existing program to support ternary nodes is straightforward
  - *i.e.*, just derive new class Ternary_Node to handle ternary operators, *e.g.*, a == b ? c : d, *etc.*

```
#include "Node.h"
class Ternary_Node : public Node {
public:
  Ternary_Node (const string &, const Tree &,
      const Tree &, const Tree &);
  virtual void print (std::ostream &) const;
private:
  const string operation_;
  Tree left_, middle_, right_; };
```


C++ Ternary_Node Implementation

```
#include "Ternary_Node.h"
Ternary_Node::Ternary_Node (const string &op,
                            const Tree &a,
                            const Tree &b,
                            const Tree &c)
  : operation_ (op), left_ (a), middle_ (b),
    right_ (c) {}

void Ternary_Node::print (std::ostream &stream) const {
  stream << this->operation_ << "("
         << this->left_ // recursive call
         << "," << this->middle_ // recursive call
         << "," << this->right_ // recursive call
         << ")";
}
```

C++ Ternary_Node Implementation (cont'd)

```
// Modified class Tree Factory
class Tree {
// add 1 class constructor
public:
  Tree (const string &, const Tree &,
    const Tree &, const Tree &)
  : node_ (new Ternary_Node (op, l, m, r)) {}
// Same as before . . .
```


Differences from Algorithmic Implementation

- On the other hand, modifying the original algorithmic approach requires changing (1) the original data structures, *e.g.*,

```
 struct Tree_Node {
  enum {
    NUM, UNARY, BINARY, TERNARY
  } tag_; // same as before
  union {
    // same as before.  But, add this:
    struct {
      Tree_Node *l_, *m_, *r_;
    } ternary_;
  } c;
#define ternary_ c.ternary_
};
```


Differences from Algorithmic Implementation (cont'd)

- & (2) many parts of the code, *e.g.*,

```
void print_tree (Tree_Node *root) {
  // same as before
  case TERNARY: // must be TERNARY.
    printf ("(");
    print_tree (root->ternary_.l_);
    printf ("%c", root->op_[0]);
    print_tree (root->ternary_.m_);
    printf ("%c", root->op_[1]);
    print_tree (root->ternary_.r_);
    printf (")"); break;
  // same as before
}
```


Summary of Expression Tree Example

- OO version represents a more complete modeling of the application domain
  - *e.g.*, splits data structures into modules that correspond to "objects" & relations in expression trees
- Use of C++ language features simplifies the design and facilitates extensibility
  - *e.g.*, implementation follows directly from design
- Use of patterns helps to motivate, justify, & generalize design choices

Potential Problems with OO Design

- Solution is very "data structure rich"
  - *e.g.*, requires configuration management to handle many headers & `.cpp` files!
- May be somewhat less efficient than original algorithmic approach
  - *e.g.*, due to virtual function overhead
- In general, however, virtual functions may be no less inefficient than large switch statements or if/else chains . . .
- As a rule, be careful of micro vs. macro optimizations
  - *i.e.*, always profile your code!

Case Study: System Sort

- Develop a general-purpose system sort
  - It sorts lines of text from standard input and writes the result to standard output
  - *e.g.*, the UNIX system sort
- In the following, we'll examine the primary forces that shape the design of this application
- For each force, we'll examine patterns that resolve it

External Behavior of System Sort

- A "line" is a sequence of characters terminated by a newline
- Default ordering is lexicographic by bytes in machine collating sequence (*e.g.*, ASCII)
- The ordering is affected globally by the following options:
  - Ignore case (`-f`)
  - Sort numerically (`-n`)
  - Sort in reverse (`-r`)
  - Begin sorting at a specified field (`-k`)
  - Begin sorting at a specified column (`-c`)
- Your program need not sort files larger than main memory

High-level Forces

- Solution should be both time & space efficient
  - *e.g.*, must use appropriate algorithms and data structures
  - Efficient I/O & memory management are particularly important
  - Our solution uses minimal dynamic binding (to avoid unnecessary overhead)
- Solution should leverage reusable components
  - *e.g.*, istd::ostreams, Array & Stack classes, *etc.*
- Solution should yield reusable components
  - *e.g.*, efficient input classes, generic sort routines, *etc.*

Top-level Algorithmic View of the Solution

- Note the use of existing C++ mechanisms like I/O streams

```
// Reusable function:
// template <typename ARRAY> void sort (ARRAY &a);

int main (int argc, char *argv[])
{
  parse_args (argc, argv);
  Input input;

  cin >> input;
  sort (input);
  cout << input;
}
```

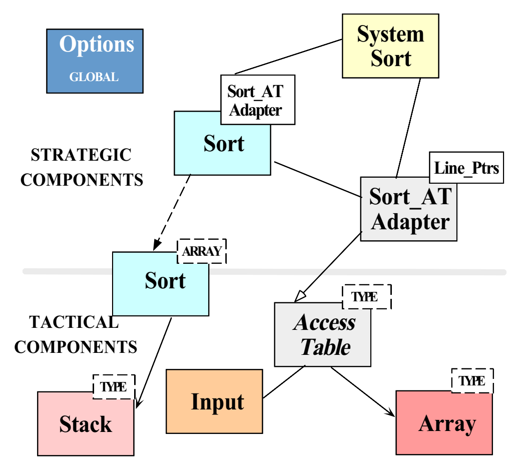

Top-level Algorithmic View of the Solution (cont'd)

- Avoid the *grand mistake* of using top-level algorithmic view to structure the design . . .
  - Structure the design to resolve the forces!
  - Don't focus on algorithms *or* data, but instead look at the problem, its participants, & their interactions!

General OOD Solution Approach

- Identify the classes in the application/problem space & solution space
  - *e.g.*, stack, array, input class, options, access table, sorts, *etc.*
- Recognize & apply common design patterns
  - *e.g.*, Singleton, Factory, Adapter, Iterator
- Implement a framework to coordinate components
  - *e.g.*, use C++ classes & parameterized types

C++ Class Model



C++ Class Components

- *Tactical components*
  - Stack
    - Used by non-recursive quick sort
  - Array
    - Stores/sorts pointers to lines & fields
  - Access_Table
    - Used to store input
  - Input
    - Efficiently reads arbitrary sized input using only 1 dynamic allocation & 1 copy

C++ Class Components

- *Strategic components*
  - System_Sort
    - Facade that integrates everything . . .
  - Sort_AT_Adapter
    - Integrates `Array` & `Access_Table`
  - Options
    - Manages globally visible options
  - Sort
    - *e.g.*, both quicksort & insertion sort

Detailed Format for Solution

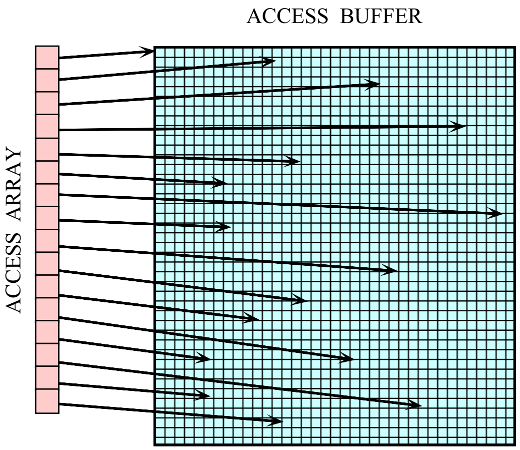
- Note the separation of concerns

```
// Prototypes
template <typename ARRAY> void sort (ARRAY &a);
void operator>> (std::istream &, Sort_AT_Adapter &);
void operator<< (std::ostream &, const Sort_AT_Adapter &);

int main (int argc, char *argv[])
{
  Options::instance ()->parse_args (argc, argv);
  cin >> System_Sort::instance ()->access_table ();
  sort (System_Sort::instance ()->access_table ());
  cout << System_Sort::instance ()->access_table ();
}
```


Reading Input Efficiently

- *Problem*
  - The input to the system sort can be arbitrarily large (*e.g.*, up to 1/2 size of main memory)
- *Forces*
  - To improve performance solution must minimize:
    1. Data copying & data manipulation
    2. Dynamic memory allocation
- *Solution*
  - Create an `Input` class that reads arbitrary input efficiently

Access Table Format



The Input Class

- Efficiently reads arbitrary-sized input using only 1 dynamic allocation

```
class Input {
public:
  // Reads from <input> up to <terminator>, replacing <search>
  // with <replace>.   Returns dynamically allocated buffer.
  char *read (std::istream &input, int terminator = EOF,
              int search = '\n', int replace = '\0');
  // Number of bytes replaced.
  size_t replaced () const;
  // Size of buffer.
  size_t size () const;
private:
  // Recursive helper method.
  char *recursive_read ();
  // . . .
};
```


The Input Class (cont'd)

```
char *Input::read (std::istream &i, int t, int s, int r)
{
  // Initialize all the data members...
  return recursive_read ();
}

char *Input::recursive_read () {
  char buffer[BUFSIZ];
  // 1.   Read input one character at a time, performing
  //      search/replace until EOF is reached or buffer
  //      is full.
  // 1.a If buffer is full, invoke recursive_read()
  //      recursively.
  // 1.b If EOF is reached, dynamically allocate chunk
  //      large enough to hold entire input
  // 2.   On way out of recursion, copy buffer into chunk
}
```


Design Patterns in the System Sort

- Facade
  - *Provide a unified interface to a set of interfaces in a subsystem*
    - Facade defines a higher-level interface that makes the subsystem easier to use
  - *e.g.*, `sort()` function provides a facade for the complex internal details of efficient sorting
- Adapter
  - *Convert the interface of a class into another interface clients expect*
    - Adapter lets classes work together that couldn't otherwise because of incompatible interfaces
  - *e.g.*, make `Access_Table` conform to interfaces expected by `sort` & istd::ostreams

Design Patterns in System Sort (cont'd)

- Factory
  - *Centralize assembly of resources needed to create objects*
  - *e.g.*, decouple initialization of `Line_Ptrs` used by `Access_Table` from their subsequent use
- Bridge
  - *Decouple an abstraction from its implementation so that the two can vary independently*
  - *e.g.*, comparing two lines to determine ordering
- Strategy
  - *Define a family of algorithms, encapsulate each one, & make them interchangeable*
  - *e.g.*, allow flexible pivot selection

Design Patterns in System Sort (cont'd)

- Singleton
  - *Ensure a class has only one instance, & provide a global point of access to it*
  - *e.g.*, provides a single point of access for the system sort facade & for program options
- Iterator
  - *Provide a way to access the elements of an aggregate object sequentially without exposing its underlying representation*
  - *e.g.*, provides a way to print out the sorted lines without exposing representation or initialization

Sort Algorithm

- For efficiency, two types of sorting algorithms are used:
  1. *Quicksort*
     - Highly time & space efficient sorting arbitrary data
     - O(n log n) average-case time complexity
     - O(n2) worst-case time complexity
     - O(log n) space complexity
     - Optimizations are used to avoid worst-case behavior
  2. *Insertion sort*
     - Highly time & space efficient for sorting "almost ordered" data
     - O(n2) average- & worst-case time complexity
     - O(1) space complexity

Quicksort Optimizations

1. *Non-recursive*
   - Uses an explicit stack to reduce function call overhead
2. *Median of 3 pivot selection*
   - Reduces probability of worse-case time complexity
3. *Guaranteed* (log n) *space complexity*
   - Always "pushes" larger partition
4. *Insertion sort for small partitions*
   - Insertion sort runs fast on almost sorted data

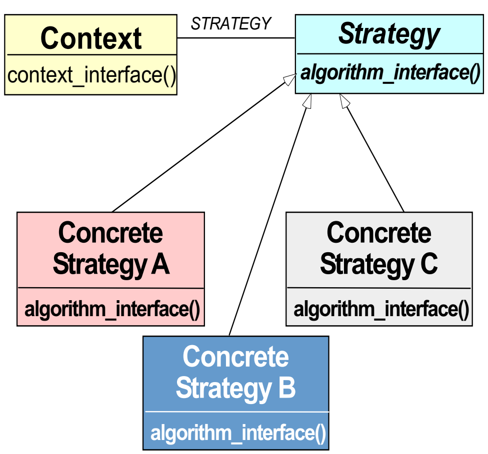
Selecting a Pivot Value

- *Problem*
  - There are various algorithms for selecting a pivot value
    - *e.g.*, randomization, median of three, *etc.*
- *Forces*
  - Different input may sort more efficiently using different pivot selection algorithms
- *Solution*
  - Use the *Strategy* pattern to select the pivot selection algorithm

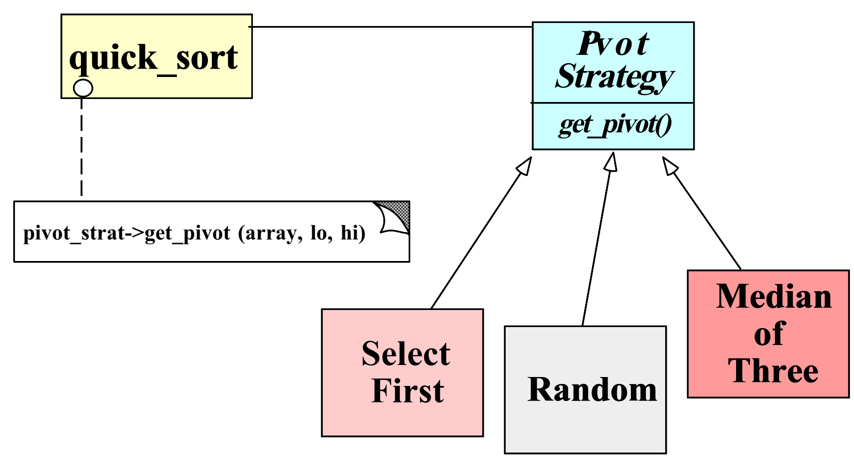
The Strategy Pattern

- *Intent*
  - Define a family of algorithms, encapsulate each one, & make them interchangeable
    - Strategy lets the algorithm vary independently from clients that use it
- This pattern resolves the following forces
  1. *How to extend the policies for selecting a pivot value without modifying the main quicksort algorithm*
  2. Provide a *one size fits all* interface without forcing a *one size fits all* implementation

Structure of the Strategy Pattern



Using the Strategy Pattern



Implementing the Strategy Pattern

- ARRAY is the particular "context"

```
template <typename ARRAY>
void sort (ARRAY &array) {
  Pivot_Strategy<ARRAY> *pivot_strat =
    Pivot_Factory<ARRAY>::make_pivot
      (Options::instance ()->pivot_strat ());
  std::auto_ptr <Pivot_Strategy<ARRAY> >
    holder (pivot_strat);

  // Ensure exception safety.
  ARRAY temp = array;
  quick_sort (temp, pivot_strat);
  // Destructor of <holder> deletes <pivot_strat>.
  array = temp;
}
```


Implementing the Strategy Pattern

```
template <typename ARRAY, class PIVOT_STRAT>
quick_sort (ARRAY &array,
            PIVOT_STRAT *pivot_strat) {
  for (;;) {
    typename ARRAY::TYPE pivot =
    // Note 'lo' & 'hi' should be passed by reference
    // so get_pivot() can reorder the values & update
    // 'lo' & 'hi' accordingly...
    pivot_strat->get_pivot (array, lo, hi);

    // Partition array[lo, hi] relative to pivot . . .
  }
}
```


Fixed-size Stack

- Defines a fixed size stack for use with non-recursive quicksort

```
template <typename T, size_t SIZE>
class Fixed_Stack
{
public:
  bool push (const T &new_item);
  bool pop (T &item);
  bool is_empty ();
  // . . .

private:
  T stack_[SIZE];
  size_t top_;
};
```

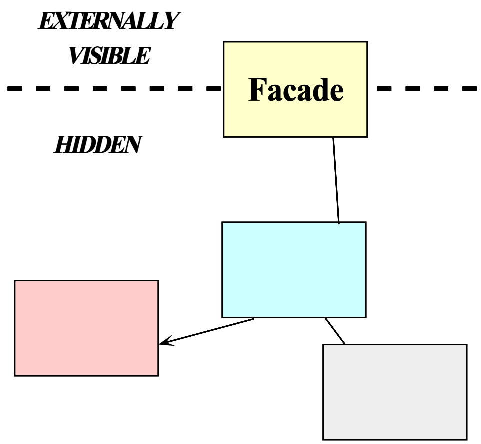

Devising a Simple Sort Interface

- *Problem*
  - Although the implementation of the `sort` function is complex, the interface should be simple to use
- *Key forces*
  - Complex interface are hard to use, error prone, and discourage extensibility & reuse
  - Conceptually, sorting only makes a few assumptions about the "array" it sorts
    - *e.g.*, supports `operator[]` methods, size, & trait TYPE
  - We don't want to arbitrarily limit types of arrays we can sort
- *Solution*
  - Use the *Facade* & *Adapter* patterns to simplify the sort program

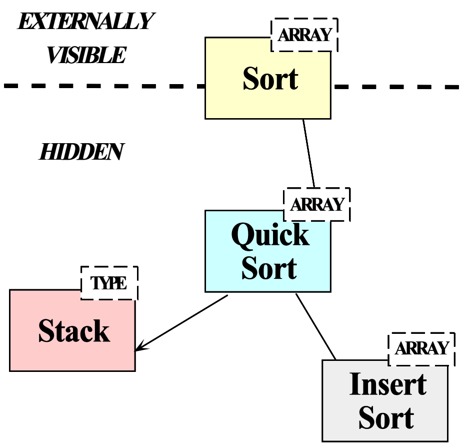
Facade Pattern

- *Intent*
  - Provide a unified interface to a set of interfaces in a subsystem
    * Facade defines a higher-level interface that makes the subsystem easier to use
- This pattern resolves the following forces:
  1. Simplifies the `sort` interface
     - *e.g.*, only need to support `operator[]` & `size` methods, & element `TYPE`
  2. Allows the implementation to be efficient and arbitrarily complex without affecting clients

Structure of the Facade Pattern



Using the Facade Pattern



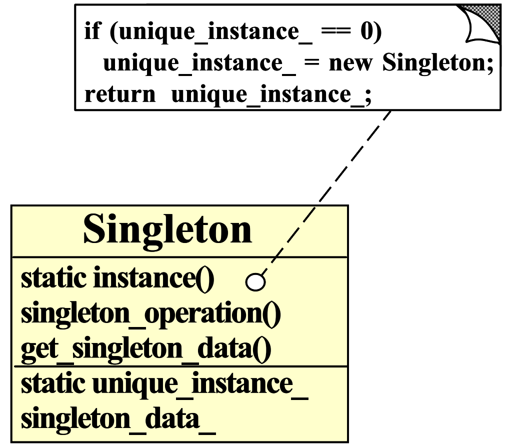
Centralizing Option Processing

- *Problem*
  - Command-line options must be global to many parts of the sort program
- *Key forces*
  - Unrestricted use of global variables increases system coupling & can violate encapsulation
  - Initialization of static objects in C++ can be problematic
- *Solution*
  - Use the *Singleton* pattern to centralize option processing

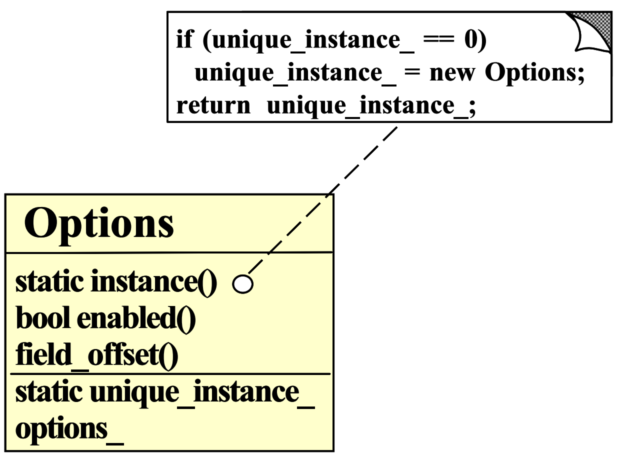
Singleton Pattern

- *Intent*
  - *Ensure a class has only one instance, & provide a global point of access to it*
- This pattern resolves the following forces:
  1. Localizes the creation & use of "global" variables to well-defined objects
  2. Preserves encapsulation
  3. Ensures initialization is done after program has started & only on first use
  4. Allow transparent subclassing of Singleton implementation

Structure of the Singleton Pattern



Using the Singleton Pattern



Options Class

- This manages globally visible options

```
class Options
{
public:
  static Options *instance ();
  bool parse_args (int argc, char *argv[]);

  // These options are stored in octal order
  // so that we can use them as bitmasks!
  enum Option { FOLD = 01, NUMERIC = 02,
                REVERSE = 04, NORMAL = 010 };
  enum Pivot_Strategy { MEDIAN, RANDOM, FIRST };
```

Options Class (cont'd)

```
  bool enabled (Option o);

  int field_offset (); // Offset from BOL.
  Pivot_Strategy pivot_strat ();
  int (*compare) (const char *l, const char *r);

protected:
  Options (); // Ensure Singleton.

  u_long options_; // Maintains options bitmask . . .
  int field_offset_;
  static Options *instance_; // Singleton.
};
```


Options Class (cont'd)

```
#define SET_BIT(WORD, OPTION) (WORD |= OPTION)
#define CLR_BIT(WORD, OPTION) (WORD &= ~OPTION)

bool Options::parse_args (int argc, char *argv[]) {
  for (int c;
       (c = getopt (argc, argv, ``nrfs:k:c:t:'')) != EOF; ) {
    switch (c) {
      case 'n': {
        CLR_BIT (options_, Options::FOLD);
        CLR_BIT (options_, Options::NORMAL);
        SET_BIT (options_, Options::NUMERIC);
        break;
      }
      // . . .
}
```


Using the Options Class

- One way to implement sort() comparison operator:

```
int Line_Ptrs::operator< (const Line_Ptrs &rhs) const {
  Options *options = Options::instance ();

  if (options->enabled (Options::NORMAL))
    return strcmp (this->bof_, rhs.bof_) < 0;

  else if (options->enabled (Options::NUMERIC));
    return numcmp (this->bof_, rhs.bof_) < 0;

  else //  if (options->enabled (Options::FOLD))
    return strcasecmp (this->bof_, rhs.bof_) < 0;
}
```

- We'll see another approach later on using Bridge

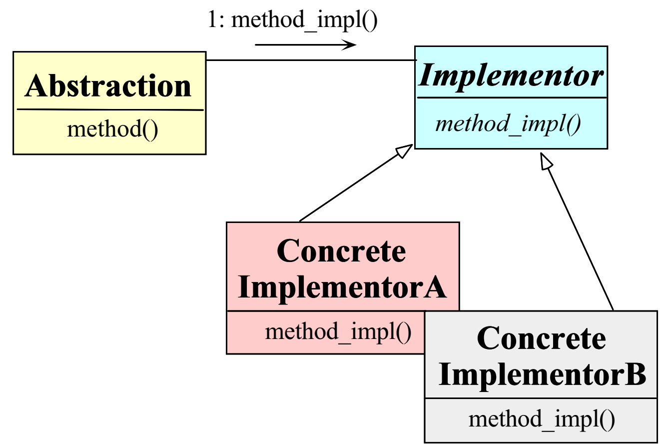
Simplifying Comparisons

- *Problem*
  - The comparison operator shown above is somewhat complex
- *Forces*
  - It's better to determine the type of comparison operation during the initialization phase
  - But the interface shouldn't change
- *Solution*
  - Use the *Bridge pattern* to separate interface from implementation

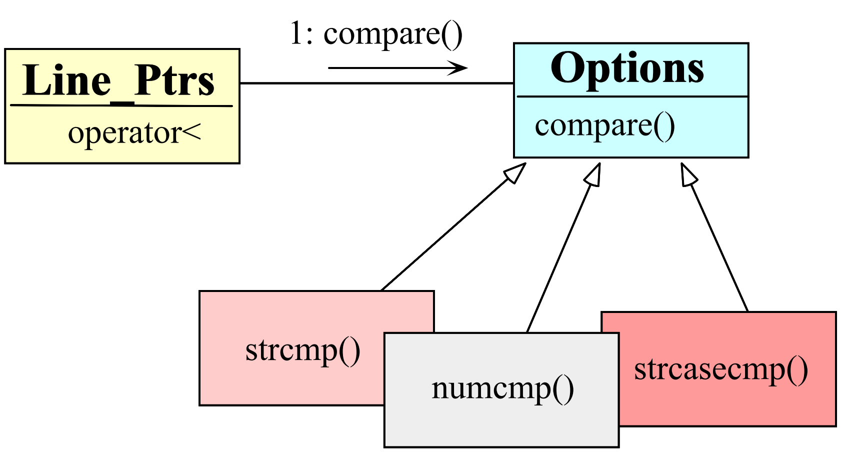
The Bridge Pattern

- *Intent*
  - *Decouple an abstraction from its implementation so that the two can vary independently*
- This pattern resolves the following forces that arise when building extensible software
  1. *How to provide a stable, uniform interface that is both closed & open, i.e.,*
     - *Closed* to prevent direct code changes
     - *Open* to allow extensibility
  2. *How to simplify the* `Line_Ptrs::operator<` *implementation & reference counting for* `Access_Table` *buffer*

Structure of the Bridge Pattern



Using the Bridge Pattern



Using the Bridge Pattern

- The following is the comparison operator used by `sort`

```
int Line_Ptrs::operator<(const Line_Ptrs &rhs) const {
  return (*Options::instance ()->compare)
            (bof_, rhs.bof_) < 0;
}
```

- This solution is much more concise
- However, there's an extra level of function call indirection . . .
  - Which is equivalent to a virtual function call

Initializing the Comparison Operator

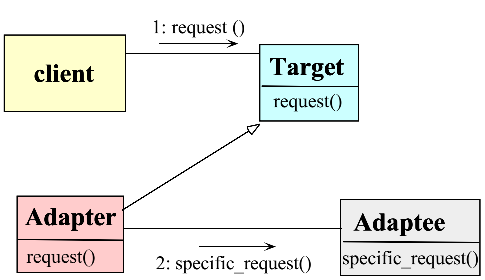
- *Problem*
  - How does the `compare` pointer-to-method get assigned? `int (*compare) (const char *left, const char *right);`
- *Forces*
  - There are many different choices for `compare`, depending on which options are enabled
  - We only want to worry about initialization details in one place
  - Initialization details may change over time
  - We'd like to do as much work up front to reduce overhead later on
- *Solution*
  - Use a *Factory* pattern to initialize the comparison operator

The Adapter Pattern

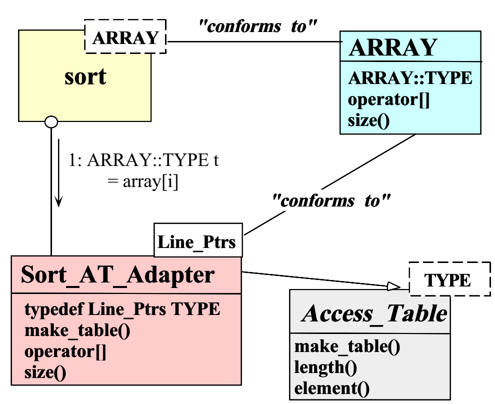
- *Intent*
  - *Convert the interface of a class into another interface clients expect*
    - Adapter lets classes work together that couldn't otherwise because of incompatible interfaces
- This pattern resolves the following forces:

1. How to transparently integrate the `Access_Table` with the `sort` routine
2. How to transparently integrate the `Access_Table` with the C++ istd::ostream operators

Structure of the Adapter Pattern



Using the Adapter Pattern



Dynamic Array

- Defines a variable-sized array for use by the Access_Table

```
template <typename T>
class Array {
public:
  Array (size_t size = 0);
  int init (size_t size);
  T &operator[](size_t index);
  size_t size () const;
  T *begin () const; // STL iterator methods.
  T *end () const;
  // . . .
private:
  T *array_;
  size_t size_;
};
```


The Access_Table Class

- Efficiently maps indices onto elements in the data buffer

```
template <typename T>
class Access_Table {
public:
  // Factory Method for initializing Access_Table.
  virtual int make_table (size_t lines, char *buffer) = 0;
  // Release buffer memory.
  virtual ~Access_Table ();
  T &element (size_t index); // Reference to <indexth> element.
  size_t length () const; // Length of the access_array.
  Array<T> &array (void) const; // Return reference to array.
protected:
  Array<T> access_array_; // Access table is array of T.
  Access_Table_Impl *access_table_impl_; // Ref counted buffer.
};
```


The Access_Table_Impl Class

```
class Access_Table_Impl { // Part of the Bridge pattern
public:
  Access_Table_Impl (void); //Default constructor
  Access_Table_Impl (char *buffer); // Constructor
  // Virtual destructor ensures subclasses are virtual
  virtual ~Access_Table_Impl (void);

  void add_ref (void); // Increment reference count
  void remove_ref (void); // Decrement reference count
  char *get_buffer(void); // Get buffer from the class
  void set_buffer(char *); // Set buffer

private:
  char *buffer_; // Underlying buffer
  size_t ref_count_; // Refcount tracks deletion.
};
```


The Sort_AT_Adapter Class

- Adapts the Access_Table to conform to the ARRAY interface expected by sort

```
struct Line_Ptrs {
  // Comparison operator used by sort().
  int operator< (const Line_Ptrs &) const;

  // Beginning of line & field/column.
  char *bol_, *bof_;
};
```

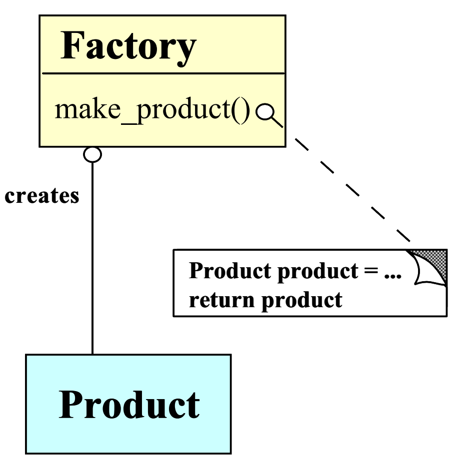
The Sort_AT_Adapter Class

```
class Sort_AT_Adapter : // Note class form of the Adapter
  private Access_Table<Line_Ptrs> {
public:
  virtual int make_table (size_t num_lines, char *buffer);

  typedef Line_Ptrs TYPE; // Type trait.

  // These methods adapt Access_Table methods . . .
  Line_Ptrs &operator[] (size_t index);
  size_t size () const;
};

// Put these into separate file.
Line_Ptrs &Sort_AT_Adapter::operator[] (size_t i)
{ return element (i); }
size_t Sort_AT_Adapter::size () const { return length (); }
```

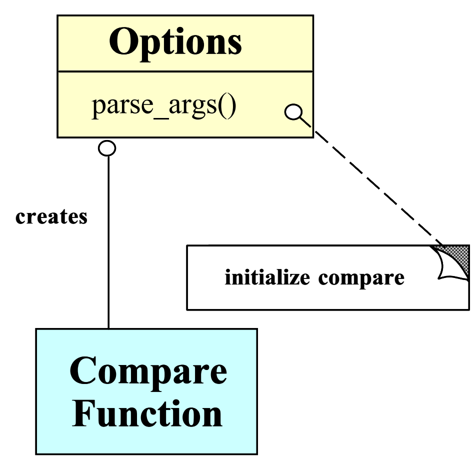

The Factory Pattern

- *Intent*
  - *Centralize the assembly of resources necessary to create an object*
    - Decouple object creation from object use by localizing creation knowledge
- This pattern resolves the following forces:
  - Decouple initialization of the `compare` operator from its subsequent use
  - Makes it easier to change comparison policies later on
    - *e.g.*, adding new command-line options

Structure of the Factory Pattern



Using the Factory Pattern for Comparisons



Code for Using the Factory Pattern

- The following initialization is done after command-line options are parsed

```
bool Options::parse_args (int argc, char *argv[])
{
  // . . .
  if (this->enabled (Options::NORMAL))
    this->compare = &strcmp;
  else if (this->enabled (Options::NUMERIC))
    this->compare = &numcmp;
  else if (this->enabled (Options::FOLD))
    this->compare = &strcasecmp;
  // . . .
```


Code for Using the Factory Pattern (cont'd)

- We need to write a `numcmp()` adapter function to conform to the API used by the `compare` pointer-to-function

```
int numcmp (const char *s1, const char * s2) {
  double d1 = strtod (s1, 0), d2 = strtod (s2, 0);

  if (d1 < d2) return -1;
  else if (d1 > d2) return 1;
  else // if (d1 == d2)
    return 0;
}
```

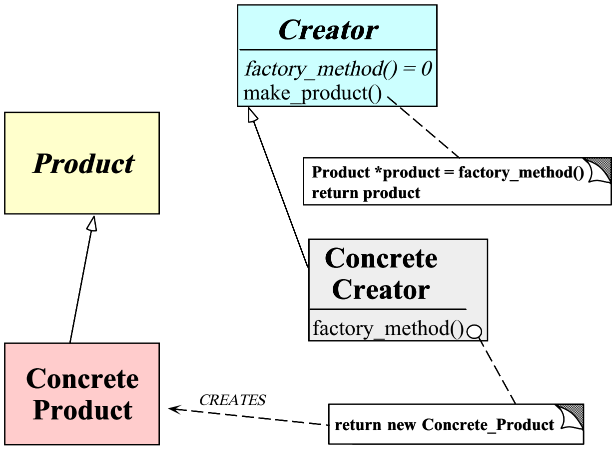

Initializing the Access_Table

- *Problem*
  - One of the nastiest parts of the whole system sort program is initializing the `Access_Table`
- *Key forces*
  - We don't want initialization details to affect subsequent processing
  - Makes it easier to change initialization policies later on
    - *e.g.*, using the Access_Table in non-sort applications
- *Solution*
  - Use the *Factory Method* pattern to initialize the `Access_Table`

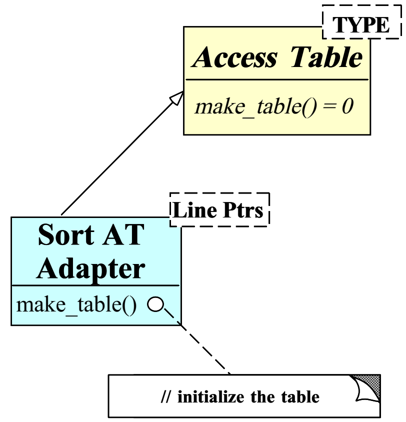
Factory Method Pattern

- *Intent*
  - Define an interface for creating an object, but let subclasses decide which class to instantiate
    - Factory Method lets a class defer instantiation to subclasses
- This pattern resolves the following forces:
  - Decouple initialization of the `Access_Table` from its subsequent use
  - Improves subsequent performance by pre-caching beginning of each field & line
  - Makes it easier to change initialization policies later on
    - *e.g.*, adding new command-line options

Structure of the Factory Method Pattern



Using the Factory Method Pattern for Access_Table Initialization



Using the Factory Method Pattern for the Sort_AT_Adapter

- The following istd::ostream Adapter initializes the `Sort_AT_Adapter` access table

```
void operator>> (std::istream &is, Sort_AT_Adapter &at)
{
  Input input;
  // Read entire stdin into buffer.
  char *buffer = input.read (is);
  size_t num_lines = input.replaced ();

  // Factory Method initializes Access_Table<>.
  at.make_table (num_lines, buffer);
}
```


Implementing the Factory Method Pattern

- The Access_Table_Factory class has a Factory Method that initializes Sort_AT_Adapter

```
// Factory Method initializes Access_Table.
int Sort_AT_Adapter::make_table (size_t num_lines,
                                 char *buffer)
{
  // Array assignment op.
  this->access_array_.resize (num_lines);
  this->buffer_ = buffer; // Obtain ownership.

  size_t count = 0;
```

Implementing the Factory Method Pattern (cont'd)

```
// Iterate through the buffer & determine
// where the beginning of lines & fields
// must go.
for (Line_Ptrs_Iter iter (buffer, num_lines);
     iter.is_done () == 0;
     iter.next ())
{
  Line_Ptrs line_ptr = iter.current_element ();
  this->access_array_[count++] = line_ptr;
}
}
```


Initializing the Access_Table with Input Buffer

- *Problem*
  - We'd like to initialize the Access_Table *without* having to know the input buffer is represented
- *Key force*
  - Representation details can often be decoupled from accessing each item in a container or collection
- *Solution*
  - Use the *Iterator* pattern to scan through the buffer

Iterator Pattern

- *Intent*
  - Provide a way to access the elements of an aggregate object sequentially without exposing its underlying representation
- The C++ Standard Library (STL) is heavily based on the iterator pattern, e.g.,

```
int main (int argc, char *argv[]) {
  std::vector <std::string> args;
  for (int i = 1; i < argc; ++i) {
      args.push_back (std::string (argv [i]));
  }
  for (std::vector<std::string>::iterator j = args.begin ();
       j != args.end (); ++j)
      cout << (*j)_ << endl;
}
```


Iterator Pattern (cont'd)

- The Iterator pattern provides a way to initialize the Access_Table without knowing how the buffer is represented

```
Line_Ptrs_Iter::Line_Ptrs_Iter (char *buffer,
                                size_t num_lines);

Line_Ptrs Line_Ptrs_Iter::current_element () {
  Line_Ptrs lp;

  // Determine beginning of next line \& next field . . .
  lp.bol_ = // . . .
  lp.bof_ = // . . .

  return lp;
}
```

Iterator Pattern (cont'd)

- Iterator provides a way to print out sorted lines

```
void operator<< (std::ostream &os, const Line_Ptrs lp) {
  os << lp.bol_;
}

void operator<< (std::ostream &os, const Sort_AT_Adapter &at) {
  if (Options::instance ()->enabled (Options::REVERSE))
    std::reverse_copy (
      at.array ().begin (),
      at.array ().end (),
      std::::ostream_iterator<System_Sort::Line_Ptrs> (os, "\n"));
  else
    std::copy (
      at.array ().begin (),
      at.array ().end (),
      std::::ostream_iterator<System_Sort::Line_Ptrs> (os, "\n"));
}
```


Summary of System Sort Case Study

- This case study illustrates using OO techniques to structure a modular, reusable, & highly efficient system
- Design patterns help to resolve many key forces
- Performance of our system sort is comparable to existing UNIX system sort
  - Use of C++ features like *parameterized types* and *inlining* minimizes penalty from increased modularity, abstraction, & extensibility

Case Study: Sort Verifier

- *Verify whether a sort routine works correctly*
  - *i.e.*, output of the sort routine must be an ordered permutation of the original input
- This is useful for checking our system sort routine!
  - The solution is harder than it looks at first glance . . .
- As before, we'll examine the key forces & discuss design patterns that resolve the forces

General Form of Solution

- The following is a general use-case for this routine:

```
template <typename ARRAY> void sort (ARRAY &a);

template <typename ARRAY> int
check_sort (const ARRAY &o, const ARRAY &p);

int main (int argc, char *argv[])
{
  Options::instance ()->parse_args (argc, argv);

  Input original;
  Input potentially_sorted;
```

General Form of Solution (cont'd)

```
  cin >> input;

  std::copy (original.begin (),
             original.end (),
             potentially_sorted.begin ());
  sort (potentially_sorted);

  if (check_sort (original, potentially_sorted) == -1)
    cerr << "sort failed" << endl;
  else
    cout << "sort worked" << endl;
}
```


Common Problems

unsorted	7	13	4	15	18	13	8	4
sorted, but not permuted	0	0	0	0	0	0	0	0
permuted, but not sorted	8	13	18	15	4	13	4	7
sorted and permuted	4	4	7	8	13	13	15	18

- Several common problems:
  - Sort routine may zero out data
    - * though it will appear sorted . . . ;-)
  - Sort routine may fail to sort data
  - Sort routine may erroneously add new values

Forces

- Solution should be both time & space efficient
  - *e.g.*, it should not take more time to check than to sort in the first place!
  - Also, this routine may be run many times consecutively, which may facilitate certain space optimizations
- We cannot assume the existence of a "correct" sorting algorithm . . .
  - Therefore, to improve the chance that our solution is correct, it must be simpler than writing a correct sorting routine
    - * *Quis costodiet ipsos custodes?*
      - · (Who shall guard the guardians?)

Forces (cont'd)

- Multiple implementations will be necessary, depending on properties of the data being examined, *e.g.*,
  1. if data values are small (in relation to number of items) & integrals use . . .
  2. if data has no duplicate values use . . .
  3. if data has duplicate values use . . .
- This problem illustrates a simple example of "program families"
  - *i.e.*, we want to reuse as much code and/or design across multiple solutions as possible

Strategies

- Implementations of search structure vary according to data, *e.g.*,
  1. *Range Vector*
     - O(N) time complexity & space efficient for sorting "small" ranges of integral values
  2. *Binary Search* (version 1)
     - O(n log n) time complexity & space efficient but does not handle duplicates
  3. *Binary Search* (version 2)
     - O(n log n) time complexity, but handles duplicates
  4. *Hashing*
     - O(n) best/average case, but O(n2) worst case, handles duplicates, but potentially not as space efficient

General OOD Solution Approach

- Identify the "objects" in the application & solution space
  - *e.g.*, use a *search structure* ADT organization with member function such as `insert` & `remove`
- Recognize common design patterns
  - *e.g.*, Strategy & Factory Method
- Implement a framework to coordinate multiple implementations
  - *e.g.*, use classes, parameterized types, inheritance & dynamic binding

General OOD solution approach (cont'd)

- C++ framework should be amenable to:
  - *Extension & Contraction*
    * May discover better implementations
    * May need to conform to resource constraints
    * May need to work on multiple types of data
  - *Performance Enhancement*
    * May discover better ways to allocate & cache memory
    * Note, improvements should be transparent to existing code . . .
  - *Portability*
    * May need to run on multiple platforms

High-level Algorithm

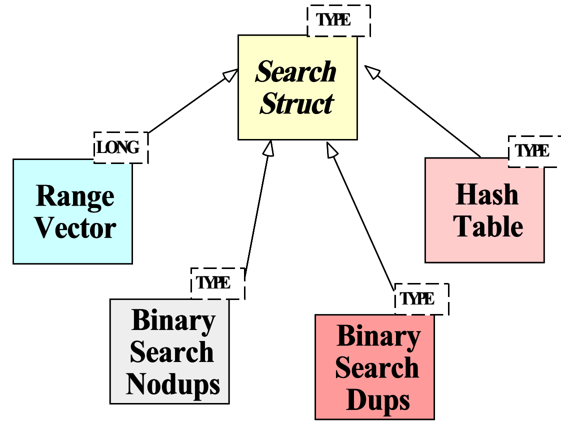
- *e.g.*, pseudo code

```
template <typename ARRAY>
int check_sort (const ARRAY &original,
    const ARRAY &potential_sort)
{
  Perform basic sanity check to see if the
    potential_sort is actually in order
    (can also detect duplicates here)
```

High-level Algorithm (cont'd)

```
    if (basic sanity check succeeds) then
      Initialize search structure, srchstrct
      for i < 0 to size - 1 loop
        insert (potential_sort[i])
          into srchstrct
      for i < 0 to size - 1 loop
        if remove (original[i]) from
           srchstrct fails then
          return ERROR
      return SUCCESS
    else
      return ERROR
    end if
  }
```


UML Class Diagram for C++ Solution



C++ Class Interfaces

- Search structure base class.

```
template <typename T>
class Search_Strategy
{
public:
  virtual bool insert (const T &new_item) = 0;
  virtual bool remove (const T &existing_item) = 0;
  virtual ~Search_Strategy () = 0;
};
```


C++ Class interfaces (cont'd)

- Strategy Factory class

```
template <typename ARRAY>
Search_Struct
{
public:
  // Singleton method.
  static Search_Struct<ARRAY> *instance ();

  // Factory Method
  virtual Search_Strategy<typename ARRAY::TYPE> *
    make_strategy (const ARRAY &);
};
```

C++ Class interfaces (cont'd)

- Strategy subclasses

```
// Note the template specialization
class Range_Vector :
  public Search_Strategy<long>
{ typedef long TYPE; /* . . . */ };

template <typename ARRAY>
class Binary_Search_Nodups :
  public Search_Strategy<typename ARRAY::TYPE>
{
  typedef typename ARRAY::TYPE TYPE; /* . . . */
};
```

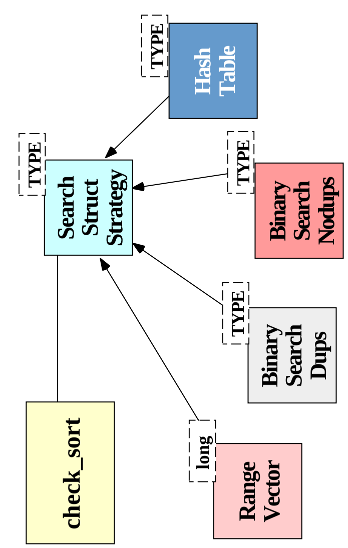

C++ Class interfaces (cont'd)

```
 template <typename ARRAY> class Binary_Search_Dups :
  public Search_Strategy<typename ARRAY::TYPE>
{
  typedef typename ARRAY::TYPE TYPE; /* . . . */
};

template <typename T>
class Hash_Table :
  public Search_Strategy<T>
{
  typedef typename ARRAY::TYPE TYPE; /* . . . */
};
```


Design Patterns in Sort Verifier

- Factory Method
  - *Define an interface for creating an object, but let subclasses decide which class to instantiate*
    - * Factory Method lets a class defer instantiation to subclasses
- In addition, the *Facade*, *Iterator*, *Singleton*, & *Strategy* patterns are used

Using the Strategy Pattern



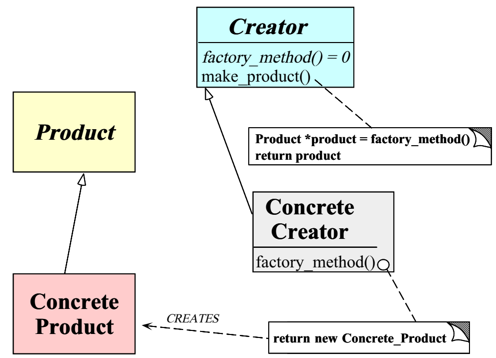
- This pattern extends the strategies for checking if an array is sorted without modifying the `check_sort` algorithm

The Factory Method Pattern

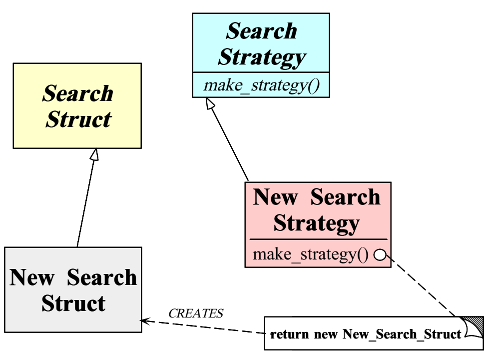
- *Intent*
  - Define an interface for creating an object, but let subclasses decide which class to instantiate
    - ∗ Factory Method lets a class defer instantiation to subclasses
- This pattern resolves the following force:

1. *How to extend the initialization strategy in the sort verifier transparently*

Structure of the Factory Method Pattern



Using the Factory Method Pattern



Implementing the check_sort Function

- *e.g.*, C++ code for the sort verification strategy

```
template <typename ARRAY> int
check_sort (const ARRAY &orig,
            const ARRAY &p_sort) {
  if (orig.size () != p_sort.size ())
    return -1;

  auto_ptr < Search_Strategy<typename ARRAY::TYPE> > ss =
    Search_Struct<ARRAY>::instance ()->make_strategy
      (p_sort);
```

Implementing the check_sort Function (cont'd)

```
  for (int i = 0; i < p_sort.size (); ++i)
    if (ss->insert (p_sort[i]) == false)
      return -1;

  for (int i = 0; i < orig.size (); ++i)
    if (ss->remove (orig[i]) == false)
      return -1;

  return 0;
  // auto_ptr's destructor deletes the memory . . .
}
```


Initializing the Search Structure

- Factory Method

```
template <typename ARRAY>
Search_Strategy<typename ARRAY::TYPE> *
Search_Struct<ARRAY>::make_strategy
  (const ARRAY &potential_sort) {
  int duplicates = 0;

  for (size_t i = 1; i < potential_sort.size (); ++i)
    if (potential_sort[i] < potential_sort[i - 1])
      return 0;
    else if (potential_sort[i] == potential_sort[i - 1])
      ++duplicates;
```


Initializing the Search Structure (cont'd)

```
  if (typeid (potential_sort[0]) == typeid (long)
      && range <= size)
    return new Range_Vector (potential_sort[0],
                             potential_sort[size - 1])
  else if (duplicates == 0)
    return new Binary_Search_Nodups<ARRAY>
                 (potential_sort);
  else if (size % 2)
    return new Binary_Search_Dups<ARRAY>
                 (potential_sort, duplicates)
  else return new Hash_Table<typename ARRAY::TYPE>
                    (size, &hash_function);
}
```


Specializing the Search Structure for Range Vectors

```
template <Array<long> > Search_Strategy<long> *
Search_Struct<Array<long> >::make_strategy
  (const Array<long> &potential_sort)
{
  int duplicates = 0;

  for (size_t i = 1; i < size; ++i)
    if (potential_sort[i] < potential_sort[i - 1])
      return 0;
    else if (potential_sort[i] == potential_sort[i - 1])
      ++duplicates;

  long range = potential_sort[size - 1] -
               potential_sort[0];
```

Specializing the Search Structure for Range Vectors

```
  if (range <= size)
    return new Range_Vector (potential_sort[0],
                             potential_sort[size - 1])
  else if (duplicates == 0)
    return new Binary_Search_Nodups<long>
                 (potential_sort);
  else if (size % 2)
    return new Binary_Search_Dups<long>
                 (potential_sort, duplicates)
  else return new Hash_Table<long>
                    (size, &hash_function);
}
```


Summary of Sort Verifier Case Study

- The sort verifier illustrates how to use OO techniques to structure a modular, extensible, & efficient solution
  - The main processing algorithm is simplified
  - The complexity is pushed into the strategy objects & the strategy selection factory
  - Adding new solutions does not affect existing code
  - The appropriate ADT search structure is selected at run-time based on the Strategy pattern