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

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Case Studies Using Patterns

- The following slides describe several case studies using C++ and patterns to build highly extensible software
- The examples include
  1. System Sort
     – *e.g.*, Facade, Adapter, Iterator, Singleton, Factory Method, Strategy, Bridge, Double-Checked Locking Optimization
  2. Sort Verifier
     – *e.g.*, Strategy, Factory Method, Facade, Iterator, Singleton

Case Study 1: 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 (**`-i`**)
  – Sort numerically (**`-n`**)
  – Sort in reverse (**`-r`**)
  – Begin sorting at a specified field (**`-f`**)
  – Begin sorting at a specified column (**`-c`**)
- Note, our program need not sort files larger than main memory

High-level Forces

- Solution should be both time and space efficient
  - *e.g.*, must use appropriate algorithms and data structures
  - Efficient I/O and memory management are particularly important
  - Our solution uses minimal dynamic binding (to avoid unnecessary overhead)
- Solution should leverage reusable components
  - *e.g.*, iostreams, Array and 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 <class ARRAY> void sort (ARRAY &a);

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

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

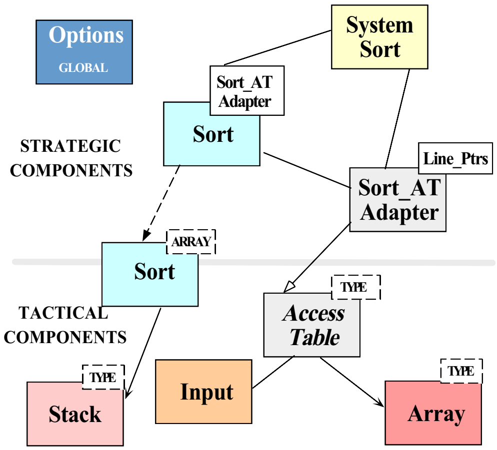

Top-level Algorithmic View of the Solution (cont'd)

- 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, and their interactions!

General OOD Solution Approach

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

C++ Class Model



C++ Class Components

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

C++ Class Components

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

Detailed Format for Solution

- Note the separation of concerns

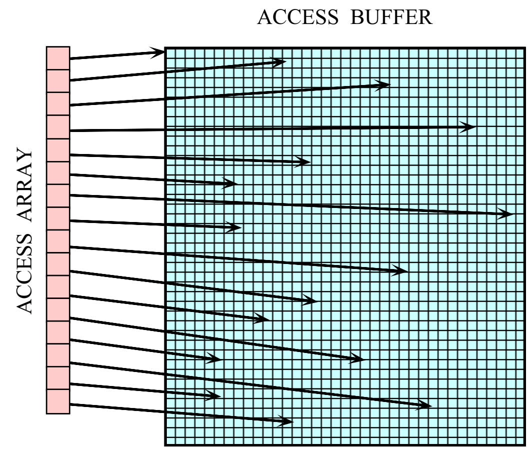
```
// Prototypes
template <class ARRAY> void sort (ARRAY &a);
void operator>> (istream &, Sort_AT_Adapter &);
void operator<< (ostream &, const Sort_AT_Adapter &);

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 and 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
  // pointer to dynamically allocated buffer.
  char *read (istream &input,
              int terminator = EOF,
              int search = '\n',
              int replace = '\0');
  // Number of bytes replaced.
  size_t replaced () const;
```


The Input Class

```
  // Size of buffer.
  size_t size () const;

private:
  // Recursive helper method.
  char *recursive_read ();

  // . . .
};
```

Design Patterns in 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`** and iostreams

Design Patterns in System Sort (cont'd)

- Factory
  - *Centralize the assembly of resources necessary to create an object*
  - *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

Design Patterns in System Sort (cont'd)

- Strategy
  - *Define a family of algorithms, encapsulate each one, and make them interchangeable*
  - *e.g.*, allow flexible pivot selection
- Singleton
  - *Ensure a class has only one instance, and provide a global point of access to it*
  - *e.g.*, provides a single point of access for the system sort facade and for program options

Design Patterns in System Sort (cont'd)

- Double-Checked Locking Optimization
  - *Ensures atomic initialization or access to objects and eliminates unnecessary locking overhead*
  - *e.g.*, allows multiple threads to execute **`sort`**
- 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 and 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 and space efficient for sorting "almost ordered" data
     - O(n2) average- and 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

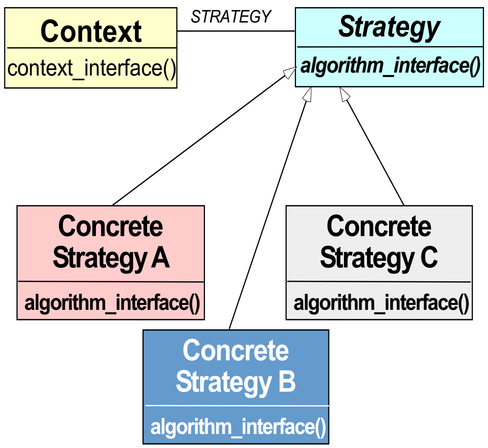
Selecting a Pivot Value

- *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

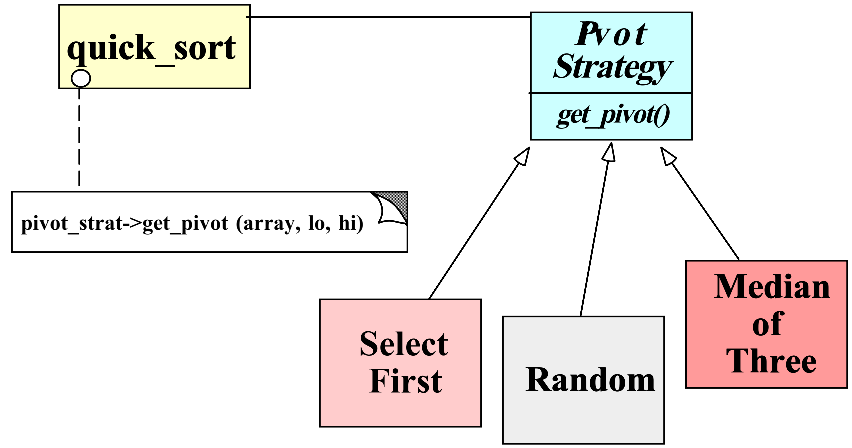
The Strategy Pattern

- *Intent*
  - Define a family of algorithms, encapsulate each one, and 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 <class ARRAY>
void sort (ARRAY &array) {
  Pivot_Factory<ARRAY> *pivot_strat =
    Pivot_Factory<ARRAY>::make_pivot
      (Options::instance ()->pivot_strat ());
  std::auto_ptr <Pivot_Factory<ARRAY> >
    holder (pivot_strat);

  quick_sort (array, pivot_strat);
  // Destructor of <holder> deletes <pivot_strat>.
}
```


Implementing the Strategy Pattern

```
template <class ARRAY, class PIVOT_STRAT>
quick_sort (ARRAY &array,
            PIVOT_STRAT *pivot_strat) {
  for (;;) {
    typename ARRAY::TYPE pivot =
      pivot_strat->get_pivot (array, lo, hi);

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

Devising a Simple Sort Interface

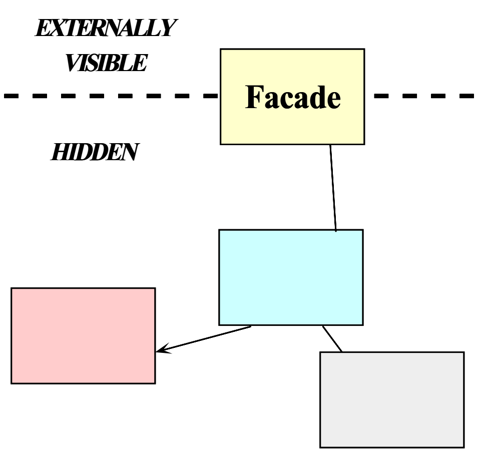
- *Problem*
  - Although the implementation of the **sort** function is complex, the interface should be simple to use
- *Key forces*
  - Complex interface are hard to use, error prone, and discourage extensibility and reuse
  - Conceptually, sorting only makes a few assumptions about the "array" it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

Facade Pattern

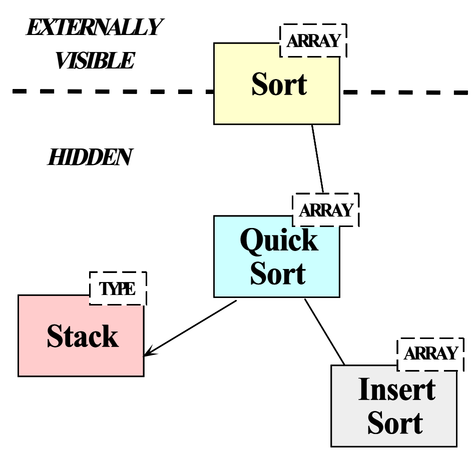
- *Intent*
  - Provide a unified interface to a set of interfaces in a subsystem
    - ∗ Facade defines a higher-level interface that makes the subsystem easier to use
- This pattern resolves the following forces:

1. Simplifies the **sort** interface
   - *e.g.*, only need to support **operator[]** and **size** methods, and element **TYPE**
2. Allows the implementation to be efficient and arbitrarily complex without affecting clients

Structure of the Facade Pattern



Using the Facade Pattern

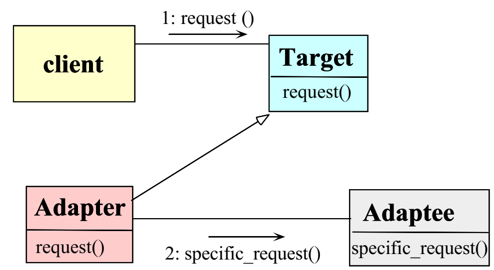


The Adapter Pattern

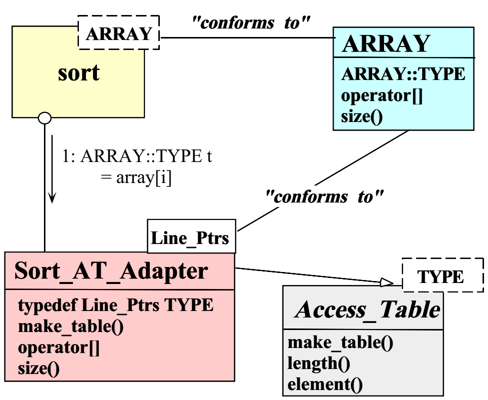
- *Intent*
  - *Convert the interface of a class into another interface clients expect*
    - Adapter lets classes work together that couldn't otherwise because of incompatible interfaces
- This pattern resolves the following forces:

1. How to transparently integrate the **`Access_Table`** with the **`sort`** routine
2. How to transparently integrate the **`Access_Table`** with the C++ iostream operators

Structure of the Adapter Pattern



Using the Adapter Pattern



Dynamic Array

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

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

The Access_Table Class

- Efficiently maps indices onto elements in the data buffer

```
template <class T>
class Access_Table {
public:
  // Factory Method for initializing Access_Table.
  virtual int make_table (size_t num_lines,
                          char *buffer) = 0;
  // Release buffer memory.
  virtual ˜Access_Table () { delete [] buffer_; }
```


The Access_Table Class (cont'd)

```
  // Retrieve reference to <indexth> element.
  T &element (size_t index) {
    return access_array_[index];
  }

  // Length of the access_array.
  size_t length () const {
    return access_array_.size ();
  }
protected:
  Array<T> access_array_; // Access table is array of T.
  char *buffer_; // Hold the data buffer.
};
```


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 and field/column.
  char *bol_, *bof_;
};
```


The Sort_AT_Adapter Class

```
 class Sort_AT_Adapter :
  // Note the use of the 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) {
    return element (index);
  }

  size_t size () const { return length (); }
};
```

Centralizing Option Processing

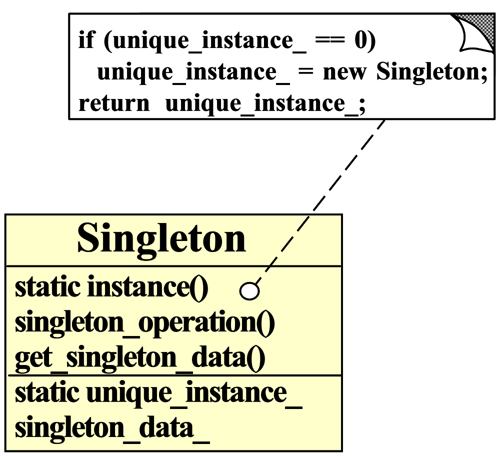
- *Problem*
  - Command-line options must be global to many parts of the sort program
- *Key forces*
  - Unrestricted use of global variables increases system coupling and can violate encapsulation
  - Initialization of static objects in C++ can be problematic
- *Solution*
  - Use the *Singleton* pattern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

Singleton Pattern

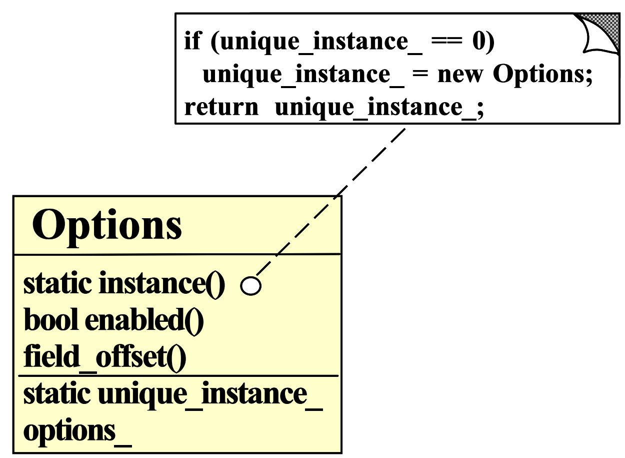
- *Intent*
  - *Ensure a class has only one instance, and provide a global point of access to it*
- This pattern resolves the following forces:

1. Localizes the creation and use of “global” variables to well-defined objects
2. Preserves encapsulation
3. Ensures initialization is done after program has started and 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 ();
  void 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

```
  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.
};
```


Using the Options Class

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

```
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;
}
```


Efficiently Avoiding Race Conditions for Singleton Initialization

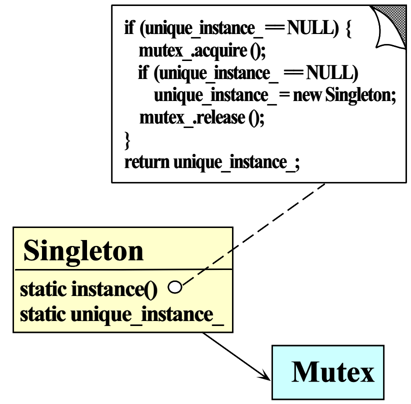
- *Problem*
  - A multi-threaded program might have execute multiple copies of **sort** in different threads
- *Key forces*
  - Subtle race conditions can cause Singletons to be created multiple times
  - Locking every access to a Singleton can be too costly
- *Solution*
  - Use the *Double-Checked Locking Optimization* pattern to efficiently avoid race conditions when initialization Singletons

The Double-Checked Locking Optimization Pattern

- *Intent*
  - *Ensures atomic initialization or access to objects and eliminates unnecessary locking overhead*
- This pattern resolves the following forces:

1. Ensures atomic initialization or access to objects, regardless of thread scheduling order
2. Keeps locking overhead to a minimum
   - *e.g.*, only lock on first access, rather than for the entire Singleton **`instance()`** method

Structure of the Double-Checked Locking Optimization Pattern



Using the Double-Checked Locking Optimization Pattern

- Uses the Adapter pattern to turn ordinary classes into Singletons optimized automatically with the Double-Checked Locking Optimization pattern

```
template <class TYPE, class LOCK>
class Singleton {
public:
  static TYPE *instance ();
protected:
  static TYPE *instance_;
  static LOCK lock_;
};
```


Using the Double-Checked Locking Optimization Pattern

```
template <class TYPE, class LOCK> TYPE *
Singleton<TYPE, LOCK>::instance () {
  // Perform the Double-Check.
  if (instance_ == 0) {
    Guard<LOCK> mon (lock_);
    if (instance_ == 0)
      instance_ = new TYPE;
  }
  return instance_;
}
```

Simplifying Comparisons

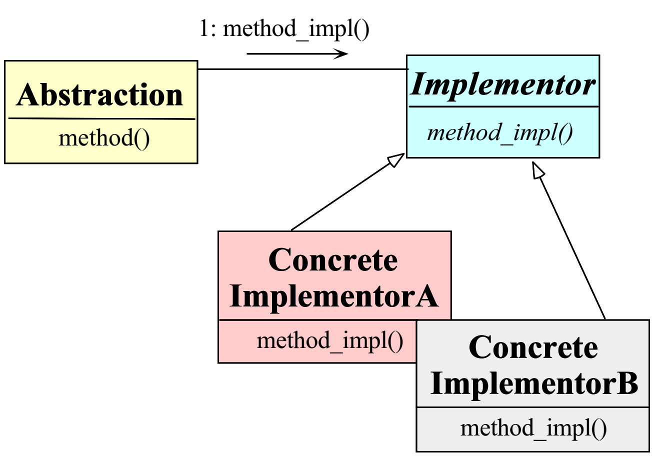
- *Problem*
  - The comparison operator shown above is somewhat complex
- *Forces*
  - It's better to determine the type of comparison operation during the initialization phase
  - But the interface shouldn't change
- *Solution*
  - Use the *Bridge pattern* to separate interface from implementation

The Bridge Pattern

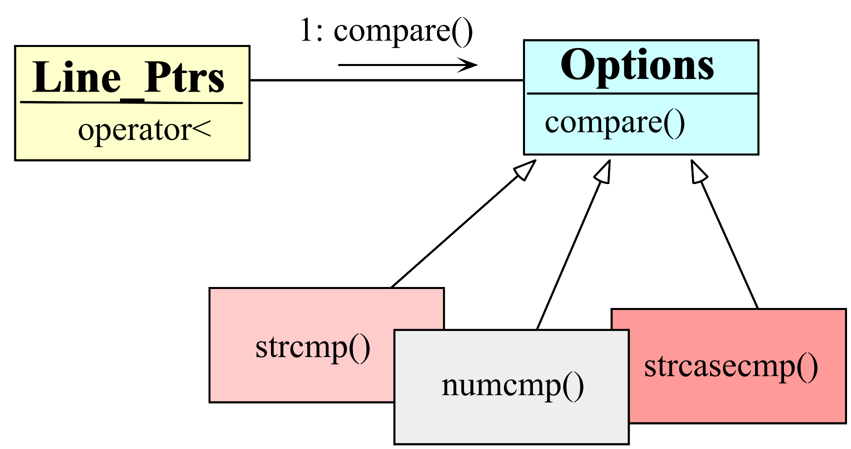
- *Intent*
  - *Decouple an abstraction from its implementation so that the two can vary independently*
- This pattern resolves the following forces that arise when building extensible software

1. *How to provide a stable, uniform interface that is both closed and open*, *i.e.*,
   - *Closed* to prevent direct code changes
   - *Open* to allow extensibility
2. *How to simplify the* **`Line_Ptrs::operator<`** *implementation*

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

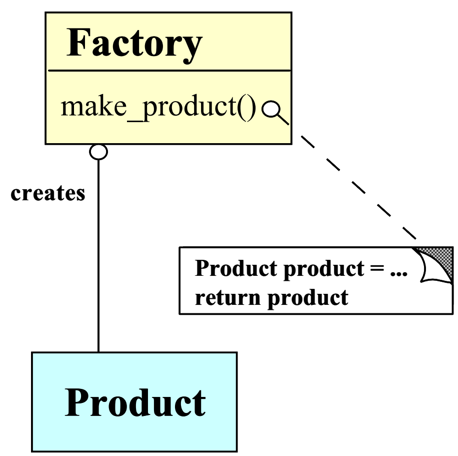
Initializing the Comparison Operator

- *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

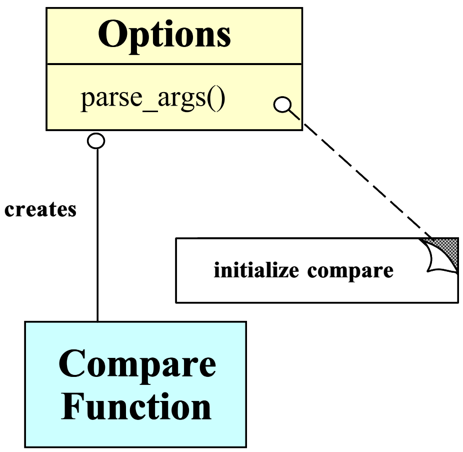
The Factory Pattern

- *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

```
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)

```
 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;
}
```

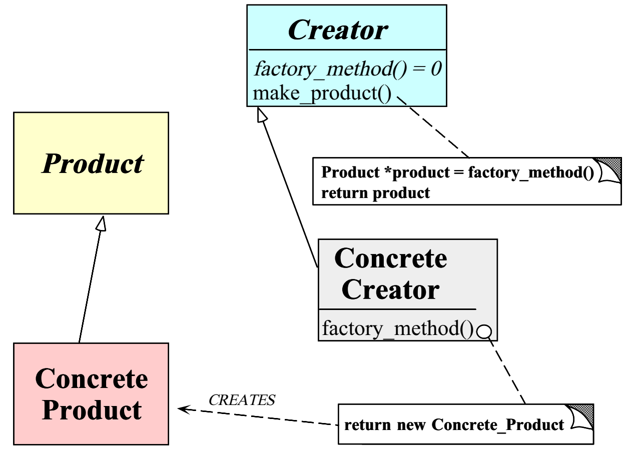

Initializing the Access_Table

- *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`**

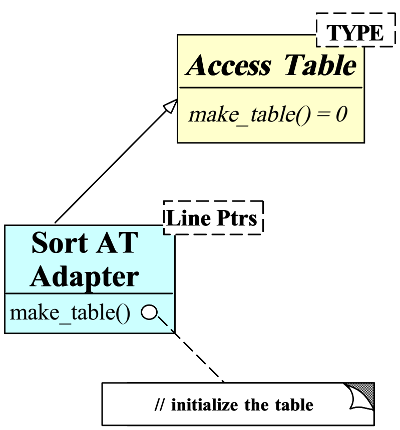
Factory Method Pattern

- *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 and 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 iostream Adapter initializes the **`Sort_AT_Adapter`** access table

```
void operator>> (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 and determine
  // where the beginning of lines and 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
- Note that STL is heavily based on iterators
- 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);
```

Iterator Pattern (cont'd)

```
Line_Ptrs Line_Ptrs_Iter::current_element () {
  Line_Ptrs lp;

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

  return lp;
}
```


Iterator Pattern (cont'd)

- The Iterator pattern also provides a way to print out the sorted lines without exposing representation

```
void operator<< (ostream &os,
                 const Sort_AT_Adapter &at)
{
  if (Options::instance ()->enabled (Options::REVERSE))
    for (size_t i = at.size (); i > 0; --i)
      os << at[i - 1]; // I/O stream adapter

  else
    for (size_t i = 0; i < at.size (); ++i)
      os << at[i]; // I/O stream adapter
}
```


Summary of System Sort Case Study

- This case study illustrates using OO techniques to structure a modular, reusable, and 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, and extensibility

Case Study 2: 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 and discuss design patterns that resolve the forces

General Form of Solution

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

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

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

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

  Input_Array input;
  Input_Array potential_sort;
```


General Form of Solution (cont'd)

```
  cin >> input;

  copy (input, potential_sort);
  sort (potential_sort);

  if (check_sort (input, potential_sort) == -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 and 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) and 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 and space efficient for sorting "small" ranges of integral values
  2. *Binary Search* (version 1)
     - O(n log n) time complexity and 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 and solution space
  - *e.g.*, use a *search structure* ADT organization with member function such as **`insert`** and **`remove`**
- Recognize common design patterns
  - *e.g.*, Strategy and Factory Method
- Implement a framework to coordinate multiple implementations
  - *e.g.*, use classes, parameterized types, inheritance and dynamic binding

General OOD solution approach (cont'd)

- C++ framework should be amenable to:
  - *Extension and 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 and cache memory
    - Note, improvements should be transparent to existing code . . .
  - *Portability*
    - May need to run on multiple platforms

High-level Algorithm

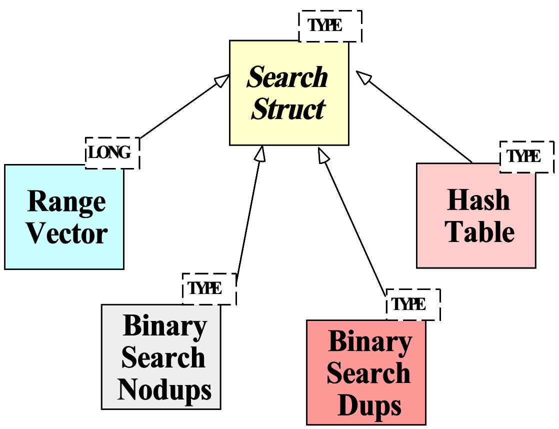
- *e.g.*, pseudo code

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

C++ Class interfaces (cont'd)

- Strategy Factory class

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


C++ Class interfaces (cont'd)

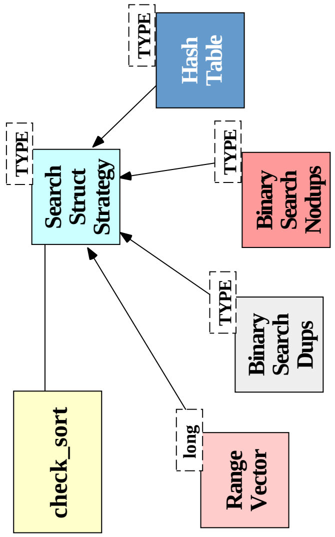
```
 template <class ARRAY> class Binary_Search_Dups :
  public Search_Strategy<typename ARRAY::TYPE>
{
  typedef typename ARRAY::TYPE TYPE; /* . . . */
};

template <class 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*, and *Strategy* patterns are used

Using the Strategy Pattern



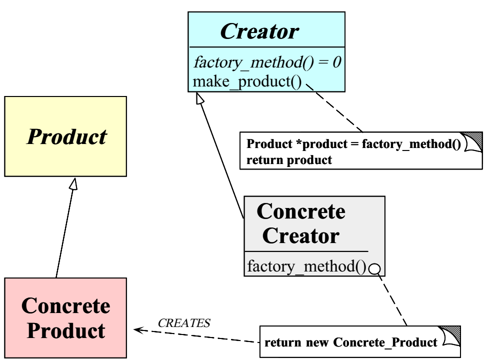
- This pattern extends the strategies for checking if an array is sorted without modifying the **check_sort** algorithm

The Factory Method Pattern

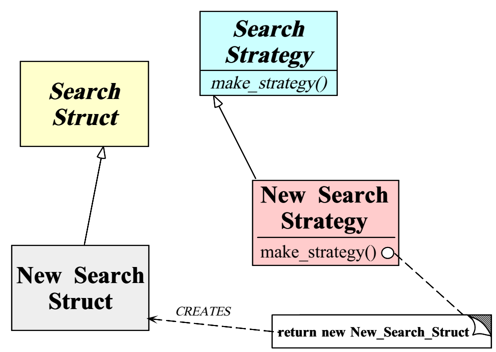
- *Intent*
  - Define an interface for creating an object, but let subclasses decide which class to instantiate
    - ∗ Factory Method lets a class defer instantiation to subclasses
- This pattern resolves the following force:

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 <class 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]) == -1)
      return -1;

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

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


Initializing the Search Structure

- Factory Method

```
template <class 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, and efficient solution
  - The main processing algorithm is simplified
  - The complexity is pushed into the strategy objects and 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