Object-Oriented Design Case Study with C++

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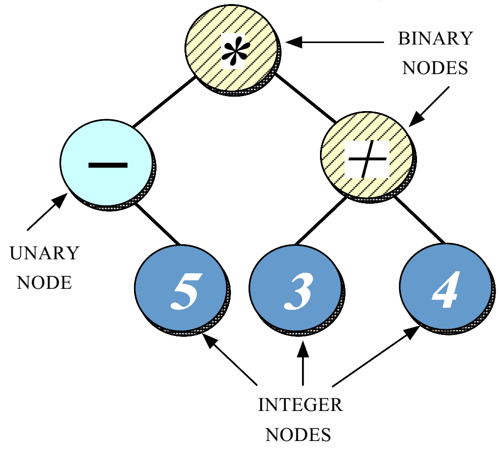
Case Study: Expression Tree Evaluator

- The following inheritance and dynamic binding example constructs *expression trees*
  - Expression trees consist of nodes containing operators and operands
    - Operators have different *precedence levels*, different *associativities*, and 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

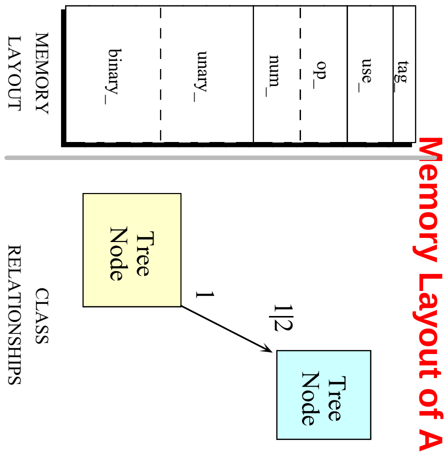
- *Expression trees*
  - Trees may be "evaluated" via different traversals
    - *e.g.*, in-order, post-order, pre-order, level-order
  - The evaluation step may perform various operations, *e.g.*,
    - Traverse and print the expression tree
    - Return the "value" of the expression tree
    - Generate 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 and a recursive function to build and 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 and 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" and functions do most processing work explicitly

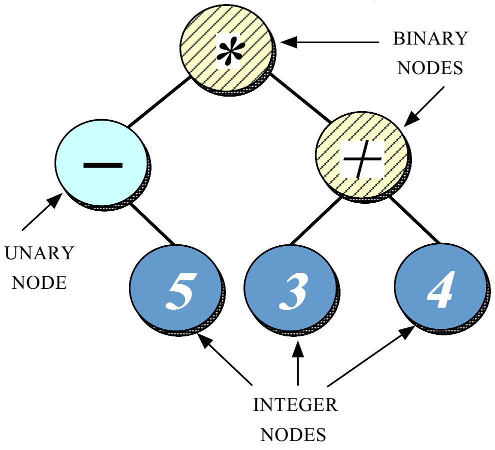
More Limitations with Algorithmic Approach

- The program organization makes it difficult to extend, *e.g.*,
  - Any small changes will ripple through the entire design and 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 and unions
  - This is not essential, but typically occurs
  - Note that this problem becomes worse the bigger the size of the largest item becomes!

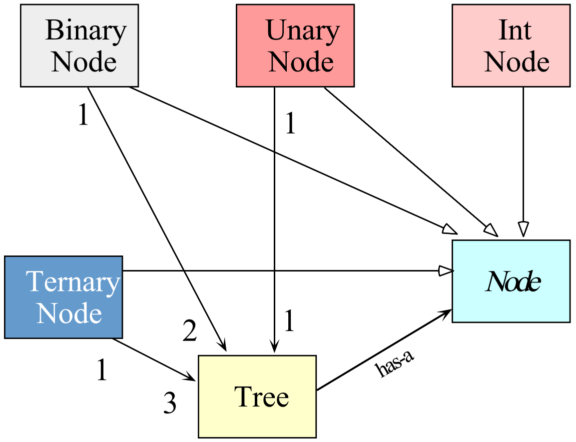
OO Alternative

- 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 and edges (vertices and arcs)

Expression Tree Diagram



Relationships Between Tree and 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 (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 (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 (ostream &stream) const;
private:
  int num_; // operand value.
};
```

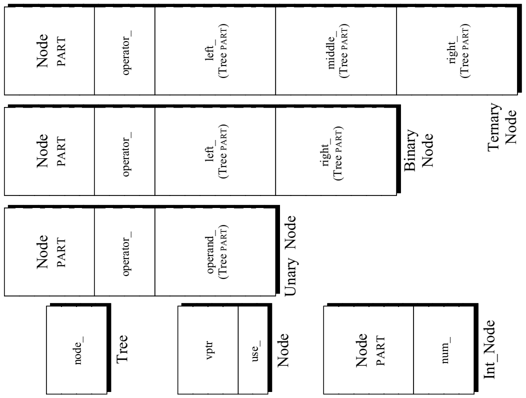
C++ Unary_Node Interface

```
 #include "Node.h"

class Unary_Node : public Node {
public:
  Unary_Node (const string &op, const Tree &t);
  virtual void print (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 (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 (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 (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 (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 and 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

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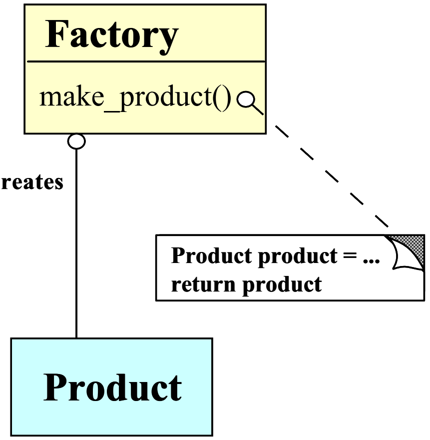
The Factory Pattern

- *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 **`Nodes`**, inheritance, and 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 and dynamic binding

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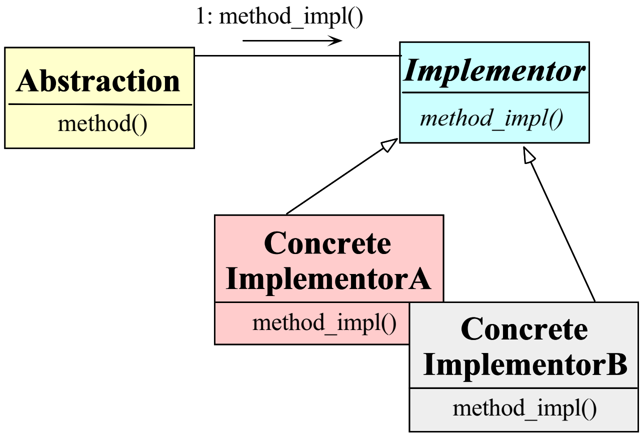
The Bridge Pattern

- *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 and 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 and robustly*
  3. *How to simplify the implementation of* **`operator<<`**

Structure of the Bridge Pattern



1: method_impl()

Abstraction

method()

Implementor

method_impl()

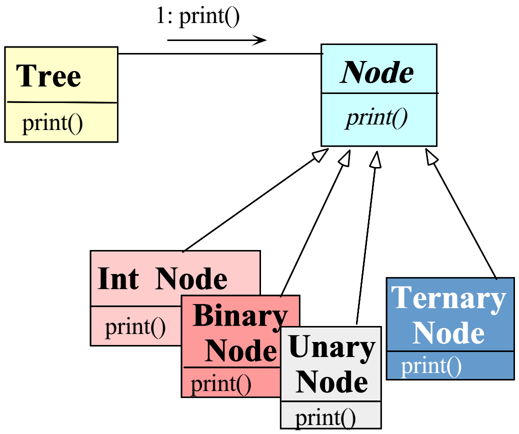
Concrete ImplementorA

method_impl()

Concrete ImplementorB

method_impl()

Using the Bridge Pattern



1: print()

Tree

print()

Node

print()

Int Node

print()

Binary Node

print()

Unary Node

print()

Ternary Node

print()

Illustrating the Bridge Pattern in C++

- The Bridge pattern is used for printing expression trees:

```
 void Tree::print (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++ iostream operators

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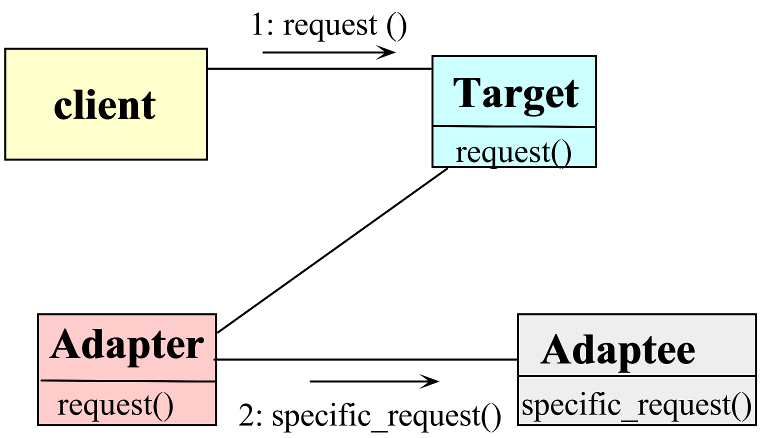
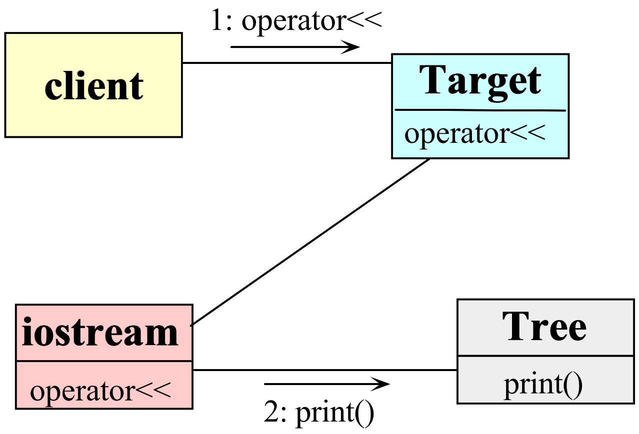
Structure of the Adapter Pattern



Using the Adapter Pattern



Using the Adapter Pattern

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

```
ostream &operator<< (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_) {
  // Sharing, ref-counting.
   ++this->node_->use_;
}

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

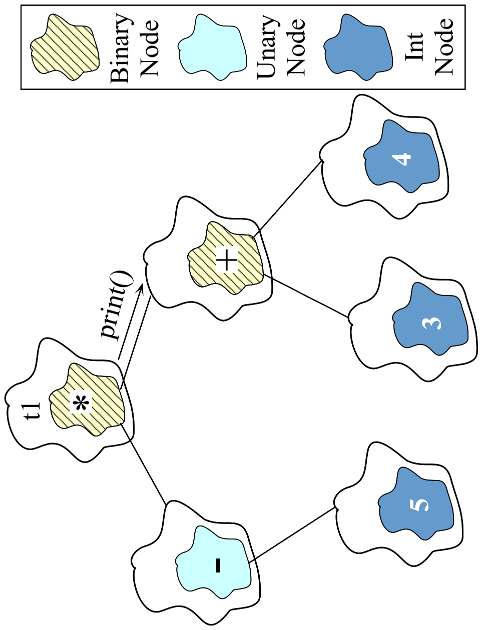
C++ Tree Implementation (cont’d)

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

C++ Main Program

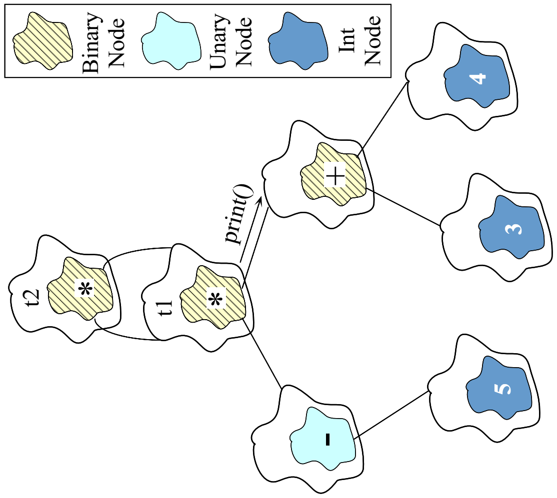
```
#include <iostream.h>
#include "Tree.h"

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 and 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 (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 (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)

- and (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" and 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, and generalize design choices

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Potential Problems with OO Design

- Solution is very "data structure rich"
  - *e.g.*, requires configuration management to handle many headers and `.cc` 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!