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Understanding C++ Expression Templates

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Objectives

What are expression templates?

- an example of using templates for runtime-efficient computations
- an example of modern template programming techniques
  - template meta-programming
  - generative programming

Where it all started ...

- Erwin Unruh's prime number program ...
  - does not compile, but
  - calculates the prime numbers at compile-time and
  - emits them in error messages.
- works via recursive template evaluation
- useful for
  - evaluation of expressions (vector dot product, matrix operations)
  - calculation of constants (square root of N, prime numbers)
  - evaluation of logical expression (more readable STL functors)

Agenda

- compile-time computation of constant values
  - factorial
  - square root
- compile-time evaluation of expressions
  - dot product
  - arithmetic expression
- more examples of modern template programming
  - compile-time polymorphism
  - policy classes
  - template meta-programming

Runtime Computation of Factorial

The factorial of *n* is $1 \cdot 2 \cdot \ldots \cdot (n-1) \cdot n$, and the factorial of *0* is *1*.

A recursive factorial function:

```
int factorial (int n)
{ return (n==0) ? 1: n*factorial(n-1); }
```

```
cout << factorial(4) << endl;
```


Compile-Time Counterpart

A class for compile time computation of the factorial:

```
template <int n>
struct Factorial {
  enum { RET = Factorial<n-1>::RET * n };
};

template <>
struct Factorial<0> {
  enum { RET = 1 };
};
```

```
cout << Factorial<4>::RET << endl;
```

Agenda

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Compile-Time Computation of Square Root

Given **N**, compute a compile-time table size **ceil(sqrt(N))**.

Example: `int table[Root<10>::root];`

Beginning of recursion:

```
template <size_t Size, size_t Low=1, size_t High=Size>
struct Root;
```

```
Root<10>  =>  Root<10,1,10>
```

The Recursion

Recursive definition of `Root::root`:

```
template <size_t Size, size_t Low, size_t High>
struct Root {
   static const size_t root =
   Root<Size,(down?Low:mean+1),(down?mean:High)>
   ::root;

   static const size_t mean = (Low+High)/2;
   static const bool down = ((mean*mean)>=Size);
};
```

```
Root<10,1,10>  =>  Root<10,1,5>
      mean = (1+10)/2 = 5
      down = (5*5>=10) = true
```


End of the Recursion

```
Root<10,1,5>  =>  Root<10,4,5>
      mean = (1+5)/2 = 3
      down = (3*3>=10) = false
```

```
Root<10,4,5>  =>  Root<10,4,4>
      mean = (4+5)/2 = 4
      down = (4*4>=10) = true
```

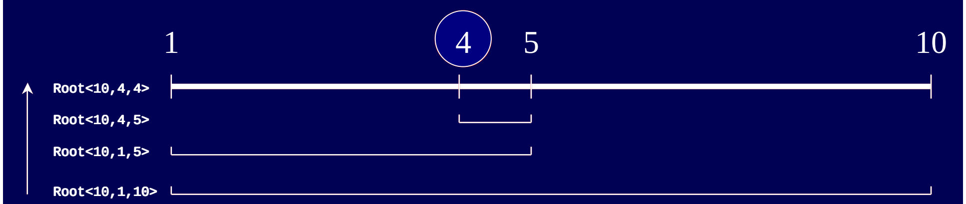
End of recursion:

```
template <size_t Size, size_t Mid>
struct Root<Size,Mid,Mid>
{ static const size_t root = Mid; };
```

Result

Given `N,` compute a compile-time table size `ceil(sqrt(N))`!

Example: `int table[Root<10>::root];`



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Goal

- efficient computation of arithmetic expressions
- example:
  - dot product of 2 vectors of dimension N

```
int a[4] = {1,100,0,-1};
int b[4] = {2,2,2,2};
dot<4>(a,b);
```

- more generally:
  - arithmetic operations on multi-dimensional matrices

More Dynamic Use

- compile-time computation of integrals

$$\int_{1.0}^{5.0} \frac{x}{1 + x}$$

```
template <class ExprT>
double integrate (ExprT e,double from,double to,size_t n)
{  double sum=0, step=(to-from)/n;
   for (double i=from+step/2; i<to; i+=step)
       sum+=e.eval(i);
   return step*sum;
}
```

```
Identity x;
cout << integrate (x/(1.0+x),1.0,5.0,10) << endl;
```

Gauss Distribution

```
double sigma=2.0, mean=5.0;
const double Pi = 3.141593;
cout << integrate(
 1.0/(sqrt(2*Pi)*sigma) * exp(sqr(x-mean)/(-2*sigma*sigma))
 ,2.0,10.0,100) << endl;
```


STL Precicates

```
list<int> l;
Identity x;
count_if(l.begin(),l.end(), x >= 0 && x <= 100 );
```

... provided the logical and comparison operators are overloaded to yield expressions that evaluation to Boolean values

- another example of expression templates
  - improve readability
  - at no additional runtime cost

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Understanding Expression Templates

- try to understand template approach as a alternative to the classic OO approach
- expressions evaluation is an example of patterns in GOF
  - composite
  - interpreter

The Composite Pattern

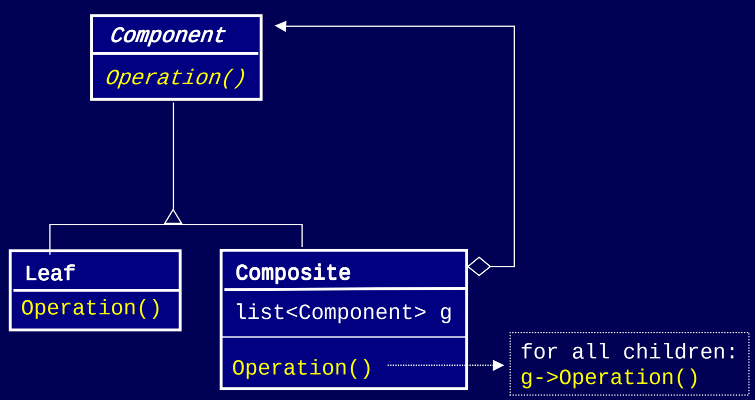
The Composite pattern provides a way to represent a part-whole relationship where the client can ignore the difference between individual objects and compositions of objects.

- The *leaf* (terminal) defines the behavior for primitive objects in the composition.
- The *composite* (non-terminal) defines the behavior for components consisting of leaves.

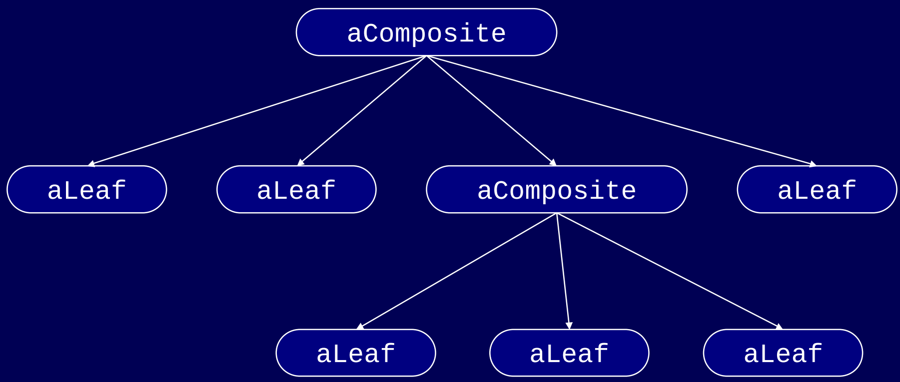
Examples:

- – syntax trees, expression evaluation
- – aggregations and recursive structures and algorithms

The Composite Pattern



A Typical Composite Structure



An Example - Vector Dot Product

Component:

– dot product of vectors of dimension N

Leaf:

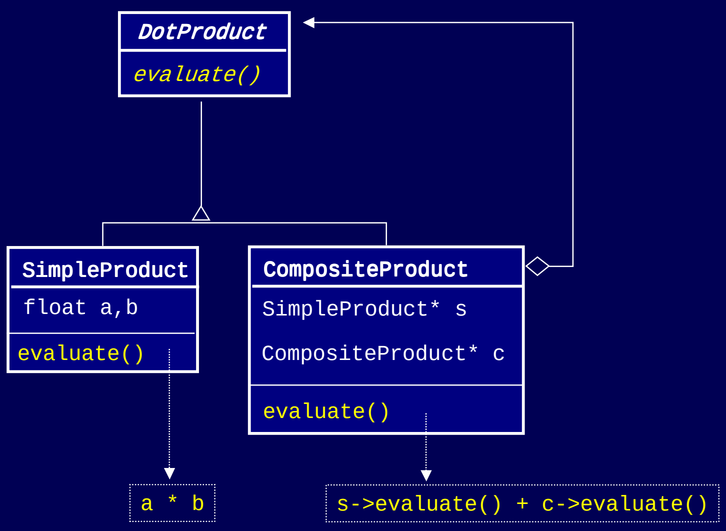
– simple product of two numerical values, i.e. the dot product of a vector of dimension 1

Composite:

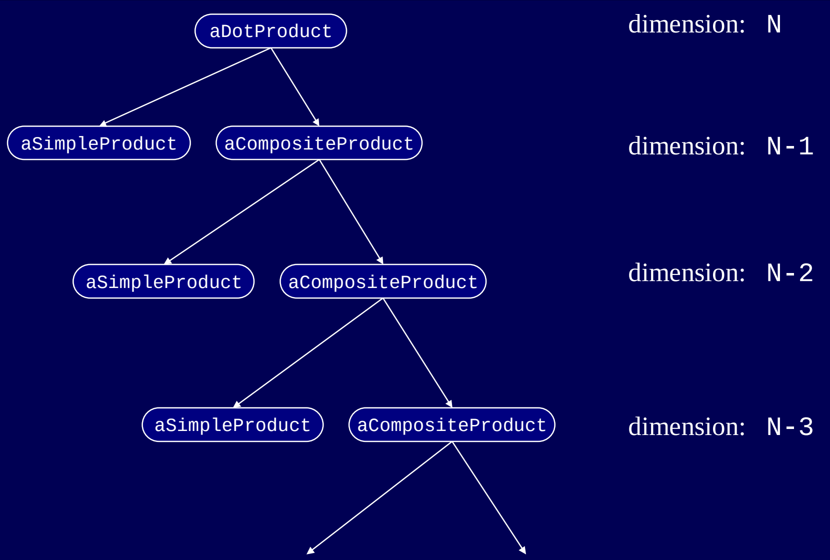
– consists of a leaf (dimension 1) and a composite (dimension N-1)

– calculation of the sum of the leaf's value and the composite's value

OO Implementation à la GOF



Composite Structure of Dot Product



The Component

The base class that defines the interface common to leaves and composites:

```
template <class T>
class DotProduct  {
   public:
      virtual ~DotProduct () {}
      virtual T eval() = 0;
};
```


The Composite

```
template <class T>
class CompositeDotProduct  : public DotProduct<T> {
public:
  CompositeDotProduct (T* a, T* b, size_t dim)
  :s(new SimpleDotProduct<T>(a,b))
  ,c((dim==1)?0:new CompositeDotProduct<T>(a+1,b+1,dim-1))
  {}
  virtual ~CompositeDotProduct () { delete c; delete s; }
  virtual T eval()
  { return (s->eval() + ((c)?c->eval():0)); }
protected:
  SimpleDotProduct<T>* s;
  CompositeDotProduct<T> * c;
};
```

The Leaf

```
template <class T>
class SimpleDotProduct  : public DotProduct <T> {
   public:
      SimpleDotProduct (T* a, T* b) :v1(a), v2(b) {}
      virtual T eval() { return (*v1)*(*v2); }
   private:
      T* v1; T* v2;
};
```


The Client

The code that initiates the recursive evaluation of the composite structure:

```
template <class T> T dot(T* a, T* b, size_t dim)
{ return (dim==1)
         ? SimpleDotProduct<T>(a,b).eval()
         : CompositeDotProduct<T>(a,b,dim).eval();
}

int a[4] = {1,100,0,-1};
int b[4] = {2,2,2,2};
dot(a,b,4);
```

A Simplified OO Implementation

Eliminate the representation of the composite and the leaf object as data members.

- Instead of passing information to the constructor and memorizing them for subsequent evaluation,
- pass them to the directly to the evaluation function.

```
SimpleDotProduct (T* a, T* b) :v1(a), v2(b) {}
virtual T eval() { return (*v1)*(*v2); }
```

becomes

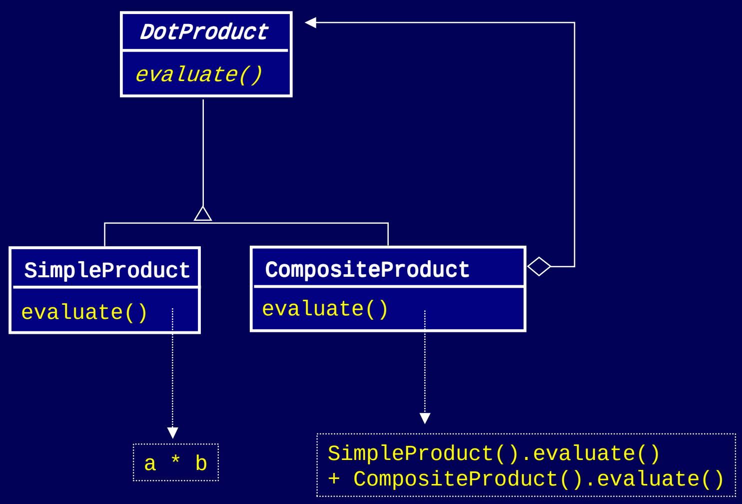
```
T eval(T* a, T* b, size_t dim) { return (*a)*(*b); }
```


A Simplified OO Implementation

```
template <class T>
class CompositeDotProduct  : public DotProduct <T> {
public:
  virtual T eval(T* a, T* b, size_t dim)
  { return  SimpleDotProduct<T>().eval(a,b,dim)
    + ((dim==1) ? 0
      : CompositeDotProduct<T>().eval(a+1,b+1,dim-1));
  }
};


template <class T>
class SimpleDotProduct  : public DotProduct <T> {
public:
  virtual T eval(T* a, T* b, size_t dim)
  { return (*a)*(*b); }
};
```

A Simplified OO Implementation



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Implementation Using Templates

- The template solution does not need a base class.
  - Eliminate the Component base class.
- Implement the Composite as a class template using structural information as template arguments.
  - The dimension of the vector becomes a non-type template argument of the Composite.
- Implement the Leaf as a specialization of the Composite.
  - The SimpleDotProduct is a specialization of the CompositeDotProduct for dimension N = 1.
- Instead of run time recursion use compile time recursion.
  - Replace the recursive invocation of the virtual evaluation function by recursive template instantiation of a static evaluation function.

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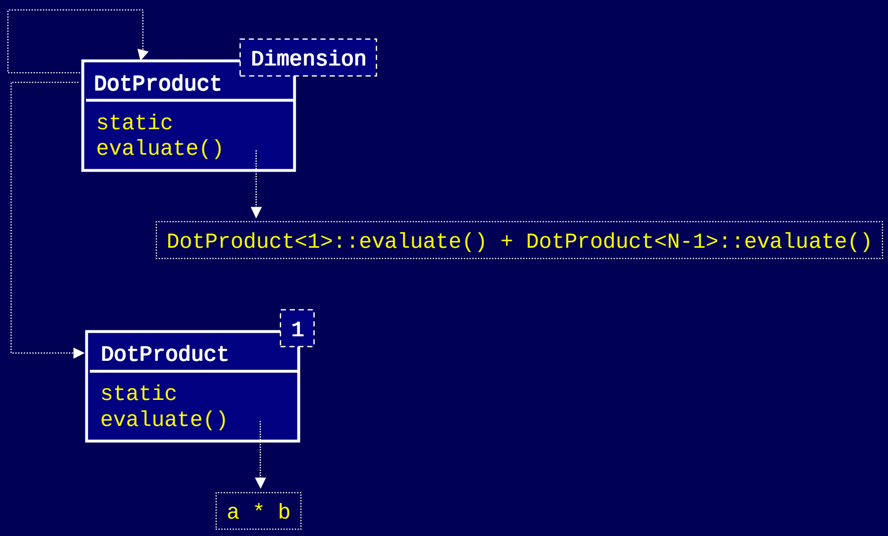
Implementation Using Templates



The Composite

```
template <size_t N, class T>
class DotProduct  {
public:
  static T eval(T* a, T* b)
  { return  DotProduct<1,T>::eval(a,b)
          + DotProduct<N-1,T>::eval(a+1,b+1);
  }
};
```

The Leaf

A specialization of the `Composite` class template for dimension N = 1:

```
template <class T>
class DotProduct<1,T> {
public:
  static T eval(T* a, T* b)
  { return (*a)*(*b); }
};
```


The Client

```
template <size_t N, class T>
T dot(T* a, T* b)
{ return DotProduct<N,T>::eval(a,b); }

int a[4] = {1,100,0,-1};
int b[4] = {2,2,2,2};
dot<4>(a,b);
```

Composite and Interpreter

The dot product example is a degenerated form of a Composite because

- every Composite consists of exactly one Leaf and and one Composite, and
- there is only one type of Leaf and one type of Composite.

The Interpreter pattern is a related pattern.

- The syntax tree in the Interpreter pattern is a Composite.

Let us discuss alternative implementations of the Interpreter pattern.

Agenda

- compile-time computation of constant values
  - factorial
  - square root
- compile-time evaluation of expressions
  - dot product
  - arithmetic expression
- more examples of modern template programming
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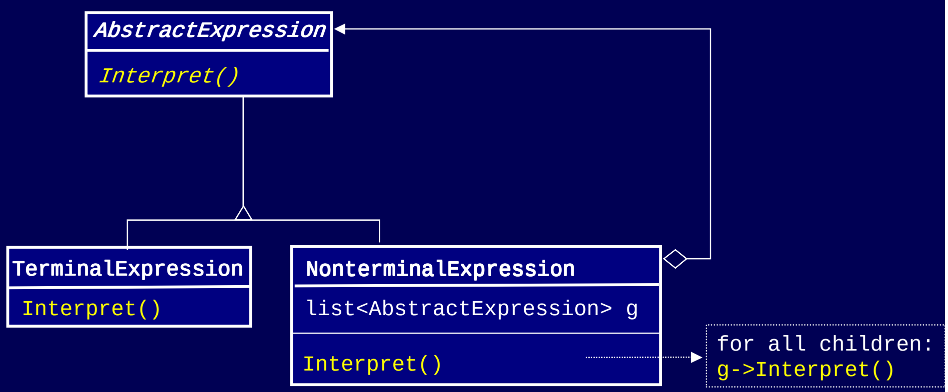
The Interpreter Pattern

The `Interpreter` pattern provides a way to represent a language in form of an abstract syntax tree and an interpreter that uses the syntax tree to interpret language constructs.

The part-whole relationship of the Composite pattern corresponds to the relationship of an expression and its subexpressions in the Interpreter pattern.

- The *leaf* is a terminal expression.
- The *composite* is a non-terminal expression.
- *Evaluation* of the components is interpretation of the syntax tree and its expressions.

The Interpreter Pattern



Example: Arithmetic Expressions

SyntaxTree:

- the representation of an arithmetic expression such as `(a+1)*c` or `log(abs(x-N))`

Terminal:

- a numerical literal such as a constant of type `double`
- a reference to a variable of type `double`;
  its value might change between interpretations of the expression

NonTerminal:

- unary and binary expression consisting of one or two subexpressions;
- the expressions have different semantics such as +, -, *, / , ++, --, exp, log, sqrt

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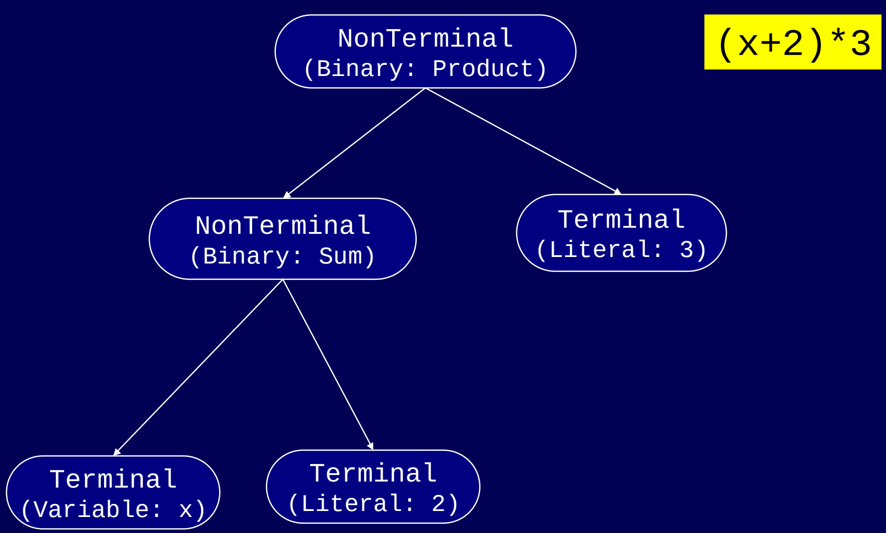
A Sample Syntax Tree



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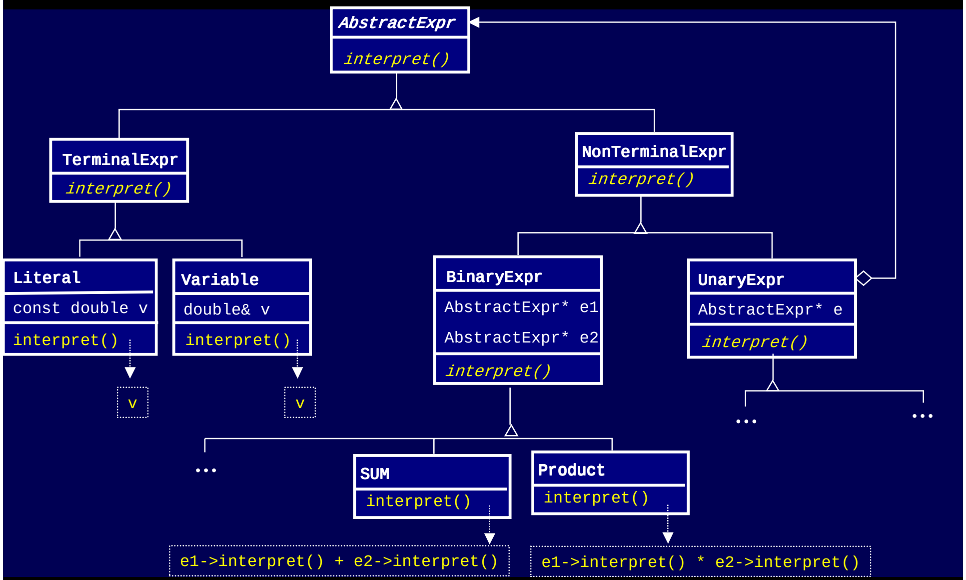
OO Implementation à la GOF



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The Abstract Expressions

The base classes that define the interface common to terminal and nonterminal expressions:

```
class AbstractExpr {
public:
    virtual double eval() const = 0;
};
```

```
class TerminalExpr : public AbstractExpr {
};
```

```
class NonTerminalExpr : public AbstractExpr {
};
```


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The Terminal Expressions

```
class Literal : public TerminalExpr {
public:
   Literal(double v) : _val(v) {}
   double eval() const { return _val; }
private:
   const double _val;
};
```

```
class Variable : public TerminalExpr  {
public:
   Variable(double& v) : _val(v) {}
   double eval() const { return _val; }
private:
   double& _val;
};
```

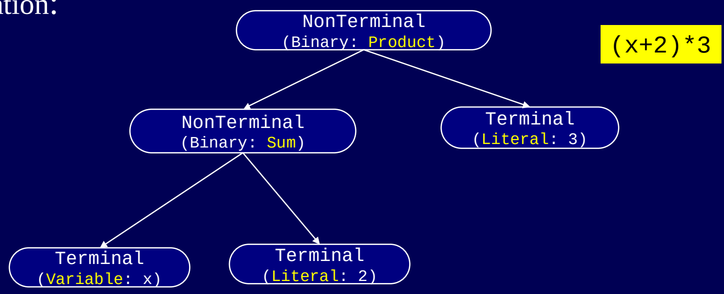

The Non-Terminal Expressions

```
class BinaryExpr : public NonTerminalExpr {
protected:
   BinaryExpr(const AbstractExpr* e1, const AbstractExpr* e2)
     : _expr1(e1),_expr2(e2) {}
   virtual ~BinaryExpr ()
   { delete const_cast<AbstractExpr*>(_expr1);
     delete const_cast<AbstractExpr*>(_expr2);
   }
   const AbstractExpr* _expr1;
   const AbstractExpr* _expr2;
};
```

```
class Sum : public BinaryExpr {
public:
   Sum(const AbstractExpr* e1, const AbstractExpr* e2)
     : BinExpr(e1,e2) {}
   double eval() const
   { return _expr1->eval() + _expr2->eval(); }
};
```

The Client

The code that creates the syntax tree and initiates its recursive interpretation:

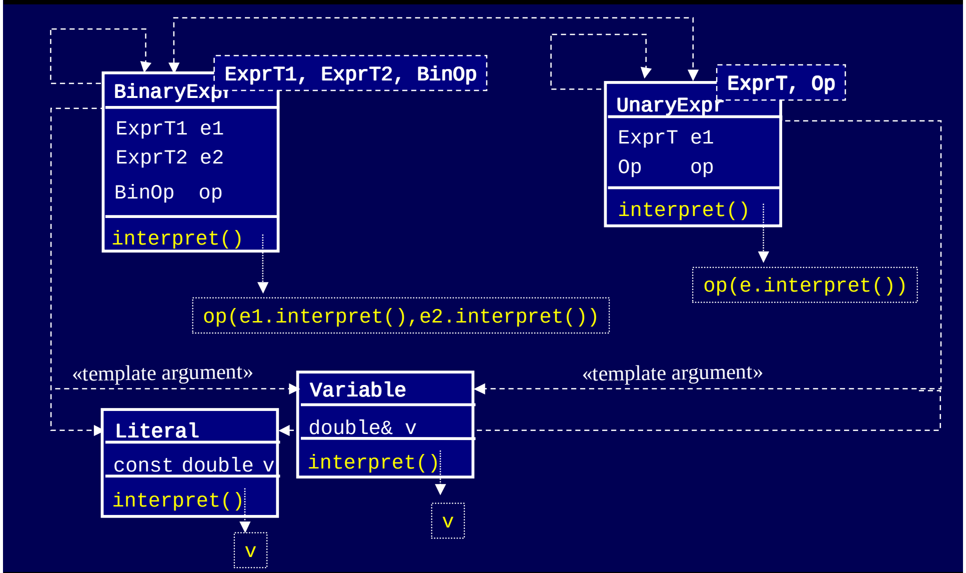



```
double x;
Product expr(new Sum(new Variable(x),new Literal(2)),
             new Literal(3));
cout << expr.eval() << endl;
```


Implementation Using Templates

- The template solution does not need a base class.
  - Eliminate all abstract base classes.
- Implement the NonTerminalExpression as a class template using structural information as template arguments.
  - The types of the subexpressions are type template arguments of the NonTerminalExpression.
- Parameterize the NonTerminalExpression with the type of operation.
  - The actual operation (+,-,*,/,++,--,abs,exp,log) is stored as a function object and its type is a template argument.
- Implement the TerminalExpressions as normal classes.
- Instead of run time recursion use compile time recursion.
  - Replace the recursive invocation of the virtual evaluation function by recursive template instantiation.

Implementation Using Templates



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The Terminal Expressions

```
class Literal {
public:
   Literal(const double v) : _val(v) {}
   double eval() const { return _val; }
private:
   const double _val;
};
```

```
class Variable {
public:
   Variable(double& v) : _val(v) {}
   double eval() const { return _val; }
private:
   double& _val;
};
```


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The Non-Terminal Expressions

```
template <class ExprT1,class ExprT2, class BinOp>
class BinaryExpr {
public:
   BinaryExpr(ExprT1 e1, ExprT2 e2,BinOp op=BinOp())
      : _expr1(e1),_expr2(e2),_op(op) {}
   double eval() const
   { return _op(_expr1.eval(),_expr2.eval()); }
private:
   ExprT1 _expr1;
   ExprT2 _expr2;
   BinOp  _op;
};
```

As operations we can use the pre-defined STL function objects `plus`, `minus`, `multiplies`, `divides`, etc. or define our own functions objects as needed.

Creator Functions

A binary expression representing a sum would be of type
`BinExpr< ExprT1, ExprT2, plus<double> >`

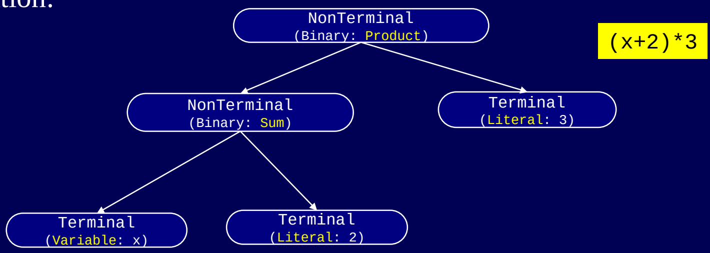
For convenience, define creator functions that take advantage of automatic template argument deduction for function templates:

```
template  <class ExprT1,class ExprT2>
BinaryExpr<ExprT1,ExprT2,plus<double> >
makeSum(ExprT1 e1, ExprT2 e2)
{ return BinaryExpr<ExprT1,ExprT2,plus<double> >(e1,e2); }
```

```
template  <class ExprT1,class ExprT2>
BinaryExpr <ExprT1,ExprT2,multiplies<double> >
makeProd(ExprT1 e1, ExprT2 e2)
{ return
   BinaryExpr<ExprT1,ExprT2,multiplies<double> >(e1,e2); }
```

The Client

The code that creates the syntax tree and initiates its recursive interpretation:




```
double x;
BinaryExpr< BinaryExpr < Variable,Literal,plus<double> >,
            Literal,
            multiplies<double> >
expr = makeProd (makeSum (Variable(x), Literal(2)),
                 Literal(3));
cout << expr.eval() << endl;
```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Operator Overloading

Often the type of the expression is not even needed:

```
double x;
cout
  << makeProd(makeSum(Variable(x),Literal(2)),Literal(3)).eval()
  << endl;
```

Take advantage of operator overloading in C++ and define the creator functions as overloaded operators.

```
Variable v(x);
cout << eval((v+2)*3.0) << endl;
```


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First attempt

Define the creator functions as overloaded operators:

```
template  <class ExprT1,class ExprT2>
BinaryExpr <ExprT1,ExprT2,plus<double> >
operator+(ExprT1 e1, ExprT2 e2)
{ return BinaryExpr <ExprT1,ExprT2,plus<double> >(e1,e2); }
```

An expression such as `x+2` would evaluate to

`BinaryExpr <double,int,plus<double> >(x,2)`

which is not exactly what we need. From just the type the compiler cannot distinguish between a literal and a variable of type `double`. We need an binary expression that stores a `Variable` and a `Literal` expression internally.

Requirement

Define variables as `Variable` expressions:

```
double x; Variable v(x);
cout << eval((v+2)*3.0) << endl;
```

The compiler can now deduce:

`BinaryExpr <Variable,int,plus<double> >(v,2)`

Inside the binary expression the variable would be stored as an expression of type `Variable` that refers to the variable `x` of type `double`.

Solution

Inside the binary expression store constants of any numerical type as `Literal` expressions.

For this purpose define for each expression type and all numerical types what their corresponding expression type is:

```
template <class ExprT> struct exprTraits
{ typedef ExprT expr_type; };

template <> struct exprTraits<double>
{ typedef Literal expr_type; };

template <> struct exprTraits<int>
{ typedef Literal expr_type; };
...
```


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Modify the BinaryExpression Class

Inside the binary expression convert expressions to their expression type as defined in the expression traits:

```
template <class ExprT1,class ExprT2, class BinOp>
class BinaryExpr {
public:
   BinaryExpr(ExprT1 e1, ExprT2 e2,BinOp op=BinOp())
      : _expr1(e1),_expr2(e2),_op(op) {}
   double eval() const
   { return _op(_expr1.eval(),_expr2.eval()); }
private:
   exprTraits<ExprT1>::expr_type _expr1;
   exprTraits<ExprT2>::expr_type _expr2;
   BinOp  _op;
};
```


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Fine Tuning

Define a helper function:

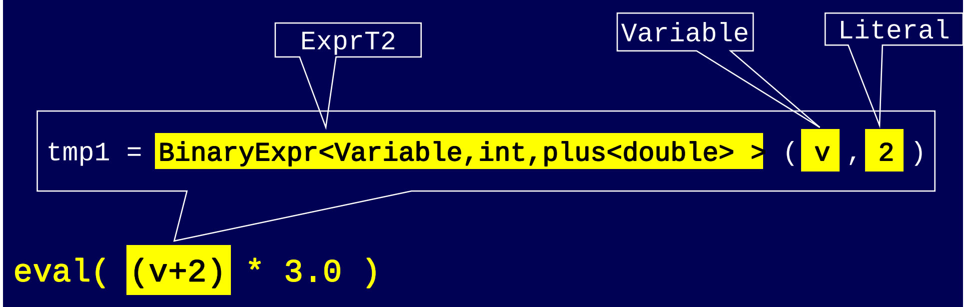
```
template <class ExprT>
double eval(ExprT e) { return e.eval(); }
```

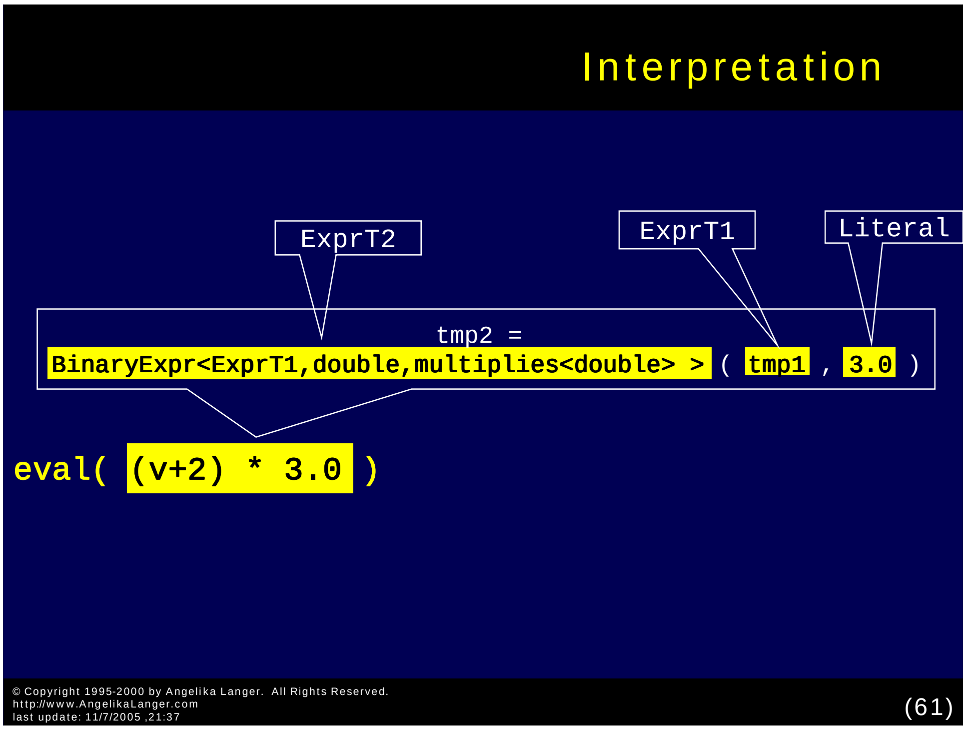
In the example

```
double x; Variable v(x);
cout << eval((v+2)*3.0) << endl;
```

the expression **`(v+2)*3.0`** evaluates to the creation of a temporary expression object and `eval()` invokes its interpretation.

Interpretation




Interpretation
ExprT2
ExprT1
Literal
tmp2 =
BinaryExpr<ExprT1,double,multiplies<double> > (tmp1 , 3.0)
eval((v+2) * 3.0)
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last update: 11/7/2005 ,21:37
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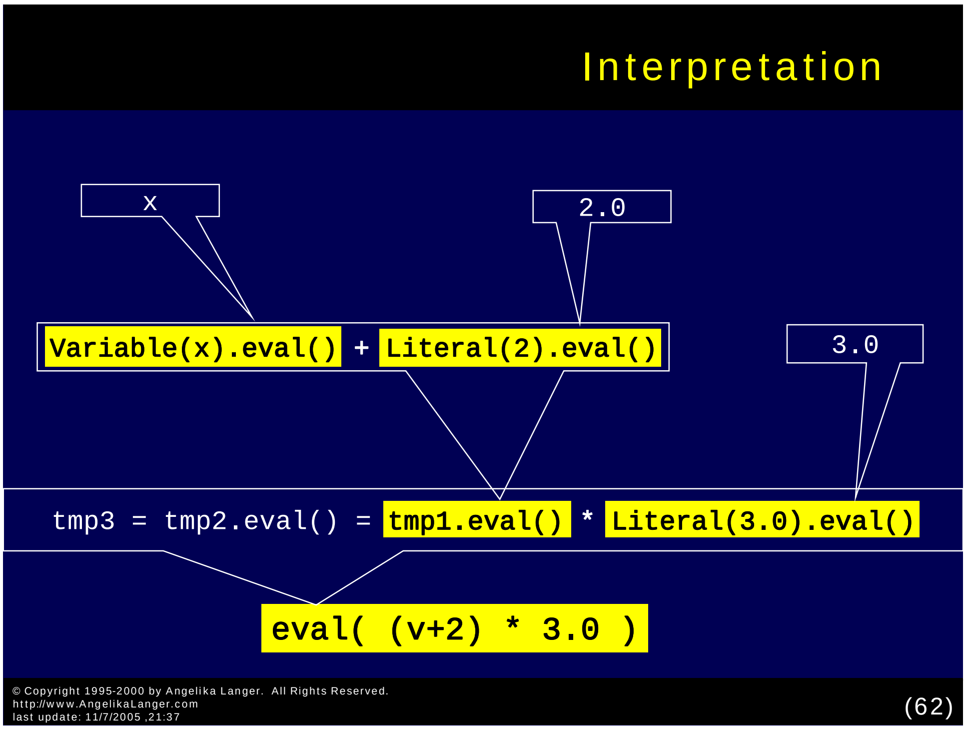
Interpretation
x
2.0
Variable(x).eval() + Literal(2).eval()
3.0
tmp3 = tmp2.eval() = tmp1.eval() * Literal(3.0).eval()
eval((v+2) * 3.0)
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last update: 11/7/2005 ,21:37
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Practical Applications

So far, the interpretation of the syntax tree is rather static.

- The syntax tree is created and interpreted only once.

A more dynamic usage model is possible, where a given syntax tree can be evaluated repeatedly for different input values.

```
template <class ExprT>
double integrate (ExprT e,double from,double to,size_t n)
{  double sum=0, step=(to-from)/n;
   for (double i=from+step/2; i<to; i+=step)
       sum+=e.eval(i);
   return step*sum;
}
```

```
Identity x;
cout << integrate (x/(1.0+x),1.0,5.0,10) << endl;
```


Minor Modifications

```
class Literal {
public:   Literal(double v) : _val(v) {}
          double eval(double) const { return _val; }
private:  const double _val;
};
```

```
class Identity {
public:   double eval(double d) const { return d; }
};
```

```
template <class ExprT1,class ExprT2, class BinOp>
class BinExpr {
public:   double eval(double d) const
          { return _op(_expr1.eval(d),_expr2.eval(d)); }
...
};
```

Incorporating Functions

We can incorporate functions such as `sqrt()`, `exp()`, etc.:

```
template  <class ExprT>
UnaryExpr<ExprT,double(*)(double)>
sqrt(const ExprT& e)
{return UnaryExpr<ExprT,double(*)(double)>(e,::std::sqrt);}
```

and calculate the Gauss distribution:

```
double sigma=2.0, mean=5.0;
const double Pi = 3.141593;
cout << integrate(
 1.0/(sqrt(2*Pi)*sigma) * exp(sqr(x-mean)/(-2*sigma*sigma))
 ,2.0,10.0,100) << endl;
```


Incorporating Functions

These functions are provided via creator functions that yield unary operations:

```
template <class ExprT, class UnaryOp>
class UnaryExpr {
public:
   UnaryExpr(ExprT e, UnaryOp op=UnaryOp())
      : _expr(e),_op(op) {}
   double eval(double d) const { return _op(_expr.eval(d)); }
private:
   exprTraits<ExprT>::expr_type _expr;
   UnaryOp  _op;
};
```

```
template  <class ExprT>
UnaryExpr<ExprT,double(*)(double)>
exp(const ExprT& e)
{ return UnaryExpr<ExprT,double(*)(double)>(e,::std::exp); }
```

Further Applications in Practice

If the `interpret()` or `eval()` function is provided as an overloaded `operator()()`, the expressions can serve as function objects for the STL.

```
list<int> l;
Identity x;
count_if(l.begin(),l.end(), x >= 0 && x <= 100 );
```

... provided the logical and comparison operators are overloaded to yield expressions that evaluation to Boolean values.

Agenda

- compile-time computation of constant values
  - factorial
  - square root
- compile-time evaluation of expressions
  - dot product
  - arithmetic expression
- more examples of modern template programming
  - compile-time polymorphism
  - policy classes
  - template meta-programming

Run-Time Polymorphism

Classic object-oriented approach:

```
class Rotatable {
public:
  virtual void rotate(int) = 0;
};

class Ellipse : public Rotatable
  {
public:
  Ellipse(int x, int y)
  : Xradius(x), Yradius(y) { }
  virtual void rotate(int);
private:  int Xradius,Yradius;
};
```


Run-Time Polymorphism

Using run-time polymorphism:

```
void vertical_flip(Rotatable& d)
{ d.rotate(180); }


Ellipse ellipse(100,600);
vertical_flip(ellipse);

Rectangle rectangle(999,500);
vertical_flip(rectangle);
```

Compile-Time Polymorphism

Replace intrusive inheritance by name commonality:

```
class Ellipse{
public: Ellipse(int x, int y)
        : Xradius(x), Yradius(y) { }
            void rotate(int);
private:  int Xradius,Yradius;
};
class Rectangle {
public: Rectangle(int x, int y)
        : Xedge(x), Yedge(y)  { }
            void rotate(int);
private:  int Xedge, Yedge;
};
```


Compile-Time Polymorphism

Using compile-time polymorphism:

```
template <class Rotatable>
void vertical_flip(Rotatable& d)
{ d.rotate(180); }


Ellipse ellipse(100,600);
vertical_flip(ellipse);

Rectangle rectangle(999,500);
vertical_flip(rectangle);
```

Run-Time vs. Compile-Time Dispatch

Inheritance-based polymorphism (OOP) can be replaced by templates (GP = generic programming).

Overhead:
- GP: code bloat & compile-time overhead
- OOP: run-time overhead

Conformance to an interface:
- GP: common names
- OOP: a common base class

Integration of built-in types:
- GP: overloaded operators <=> native operators
  function objects <=> function pointers
- OOP: not possible

Agenda

- compile-time computation of constant values
  - factorial
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  - dot product
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- more examples of modern template programming
  - compile-time polymorphism
  - policy classes
  - template meta-programming

Policy Specifications

- classic quick sort function from C library
  – uses function pointer for sorting criterion

```
void qsort( void *base, size_t num, size_t width,
  int (*compare )(const void *elem1, const void *elem2 )
   );
```

- sort algorithm from the C++ library
  – uses comparitor type (function pointer or function object)

```
template<class RandomAccessIterator, class Comparator>
void sort(RandomAccessIterator first,
          RandomAccessIterator last,
          Comparator cmp);
```


The Strategy Pattern

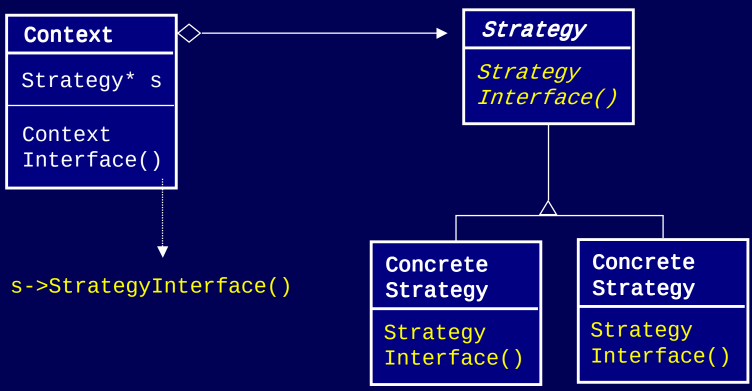
The Strategy pattern (also known as Policy) provides a way to configure a class or function (the *context*) with one of many behaviors (the *strategies*).

- There is a family of strategies that have a certain interface in common.
- The context uses this interface for implementing its operations.

Examples:

– allocation strategies of a container
– sorting order used by a sort algorithm or a sorted collection
– synchronization policy of objects

The Strategy Pattern

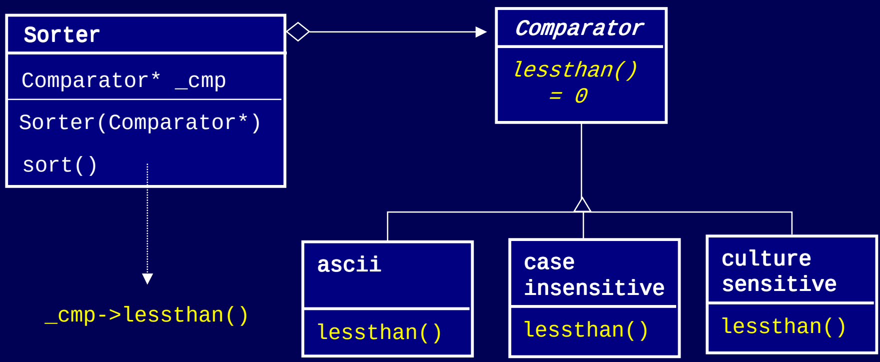


An Example - Sorting of Strings

Context:
- a class or function that sorts strings, or
- a sorted collection

Strategy:
- ASCII sorting order
- case-insensitive sorting order
- culture-sensitive, dictionary sorting order

OO Implementation à la GOF



The Context

```
class Sorter
{
public:
   explicit Sorter(Comparator* c) : _cmp(c) {}

   void sort(const StringContainer& c)
   { ... _cmp->lessthan(lhs,rhs) ... }

private:
   Comparator* _cmp;
};
```

The Strategies

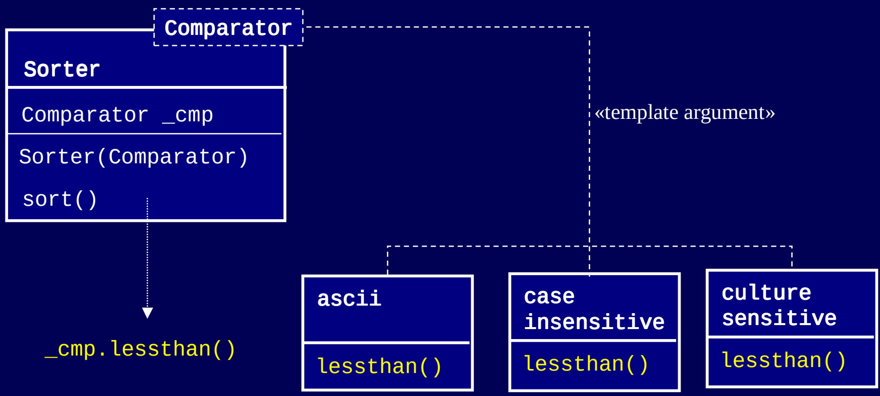
```
class Comparator {
public:
   virtual bool
   lessthan(const string&, const string&) const = 0;
};

class Ascii : public Comparator {
public:
   virtual bool
   lessthan(const string& lhs, const string& rhs) const
   { return lhs < rhs; }
};
```


Using Context and Strategies

```
StringContainer cont;
Ascii      asciiCmp;
CaseInsens caseInsCmp;
Sorter asciiSrt(&asciiCmp);
Sorter caseInsSrt(&caseInsCmp);
asciiSrt.sort(cont);
caseInsSrt.sort(cont);
```

- cannot tell from the type of the `Sorter` how it sorts
- need not re-compile `Sorter` when new strategies are added
- run time binding for `lessthan()` based on type of comparator
- polymorphism through "another level of indirection"

Implementation Using Templates



The Context

```
template <typename Comparator>
class Sorter
{
public:
   explicit Sorter(const Comparator& c = Comparator())
   : _cmp(c) {}

   void sort(const StringContainer& c)
   { ... _cmp.lessthan(lhs,rhs) ... }

private:
   Comparator _cmp;
};
```

The Strategies

```
class Ascii {
public:
   bool
   lessthan(const string& lhs, const string& rhs) const
   { return lhs < rhs; }
};
class CaseInsens {
public:
   static bool
   lessthan(const string& lhs, const string& rhs)
   {  locale loc;
      const ctype<char>& fac = use_facet<ctype<char> >(loc);
      string tmp1(lhs),tmp2(rhs);
      fac.tolower(tmp1.begin(),tmp1.end());
      fac.tolower(tmp2.begin(),tmp2.end());
      return tmp1 < tmp2;
   }
};
```


The Strategies

```
class CultSens {
public:
   explicit CultSens(locale l = locale()) : _loc(l) {}
   bool lessthan(const string& lhs, const string& rhs) const
   { return _loc(lhs,rhs); }
private:
   locale _loc;
};
```

Using Context and Strategies

```
StringContainer cont;

Sorter<Ascii>       srt1;
Sorter<CaseInsens> srt2;
Sorter<CultSens>    srt3(CultSens(locale("German")));

srt1.sort(cont);
srt2.sort(cont);
srt3.sort(cont);
```

- can tell from the name of the type of the `Sorter` how it sorts
- need to compile instantiations of `Sorter` for new strategies
- compile time binding for `sort()` and `lessthan()`
- polymorphism through templates

Evaluation of Policy Specifications

- policy specification via template parameters is more flexible
  - not restricted to just one function signature
  - both function pointers and function objects allowed
  - possibility for bundling policies

Examples from Standard C++

- sorting strategy and allocation policy of containers

```
template <class ElementType,
          class Comparator = less<Key>,
          class Allocator  = allocator<Key> >
class set;
```

- character handling and allocation policy of strings

```
template<class CharacterType,
         class CharacterTraits = char_traits<charT>,
         class Allocator = allocator<charT> >
class basic_string;
```


A Sorting Strategy

- comparator type `less` from the STL
  – just one functionality provided
  – via overloaded function call operator

```
template <class T>
struct less : binary_function<T,T,bool> {

   bool operator()(const T& x, const T& y) const;

};
```

A Policy Bundle

- the standard allocator
  - a bundle of functionalities
  - provided as non-static member functions

```
template <class T> class allocator {
public:
 ...

 pointer allocate(size_t);
 void deallocate(T* p, size_t n);

 void construct(T* p, const T& val);
 void destroy(T* p);
};
```


Another Policy Bundle

- the standard character traits for type `char`
  - a bundle of static functionality

```
template<>
struct char_traits<char> {
  static bool eq(const char& c1, const char& c2);
  static bool lt(const char& c1, const char& c2);

  static char* move(char* s1, const char* s2, size_t n);
  static char* copy(char* s1, const char* s2, size_t n);

  ...
};
```

Alexandrescu's Smart Pointer

- the configurable smart pointer class template from the Loki library
  – uses not just template type parameters, but also template template parameters

```
template
<
 typename T,
 template <class> class OwnershipPolicy = RefCounted,
 class ConversionPolicy = DissallowConversion,
 template <class> class CheckingPolicy = AssertCheck,
 template <class> class StoragePolicy = Default SPStorage
>
class SmartPointer;
```


Alexandrescu's Smart Pointer

- ownership policy
  – deep copy, destructive copy, no copy
  – reference counted (thread-safe or not)
- conversion policy
  – allow or disallow implicit conversion to underlying pointer type
- checking policy
  – reject null
  – no check
- storage policy
  – default storage (does `delete`)
  – array storage (does array `delete[]`)
  – heap storage (calls `free()`)

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Benefits of Meta-Programming

Very good performance due to

- exclusive use of static binding;
  polymorphic behavior can be simulated statically.
- inlining;
  enables the compiler to optimize aggressively.

Problems with Meta-Programming

- Debugging.
  practically not possible; there are tricks though.
- Error reporting.
  no influence on the compiler message.
- Readability of code.
  it looks awkward.
- Compilation times.
  increases by orders of magnitude.
- Compiler limits.
  truncation of identifiers, loop limits exceeded.
- Portability.
  some compilers still not support standard C++

References

Expression Template Libraries

The Blitz Project

http://oonumerics.org/blitz/

A C++ class library for scientific computing which uses template techniques to achieve high performance.

PETE (Portable Expression Template Engine)

http://www.acl.lanl.gov/pete/

A portable C++ framework to easily add powerful expression templates.

References

Expression Template Libraries

POOMA (Parallel Object-Oriented Methods and Applications)
http://www.acl.lanl.gov/pooma/

- An object-oriented framework for applications in computational science requiring high-performance parallel computers.
- Considerable success in real applications including gyrokinetic particle-in-cell plasma simulation and multimaterial compressible hydrodynamics.
- Developed at Los Alamos National Laboratory, New Mexico.

References

Further Links

Research Centre Jülich

http://www.fz-juelich.de/zam/cxx/

An impressive directory of C++ resources such as books, articles, FAQs, other C++ pages, compilers, libraries, etc.

See in particular the links to other C++ libraries at http://www.fz-juelich.de/zam/cxx/extmain.html#lib

References

Patterns

Design Patterns

Erich Gamma, Richard Helm, Ralph Johnson, John Vlissides
Addison-Wesley, 1994

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