BOOST
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Boost Metaprogramming Concepts & Frameworks

BoostCon 2007 Edition

Dave Abrahams, Boost Consulting

Agenda

- The What, Why, and How
- Tour of Boost Metaprogramming Library (MPL)
- Using MPL for Dimensional Analysis
- Expression Templates
- Building Finite State Machines
- Tuple Metaprogramming
- Preprocessor Metaprogramming

Hidden Agenda

- Functional Programming
- The Role of Polymorphism
- Type Systems
- Domain Specific Languages (DSLs)
- Embedded DSLs

“Meta:”

- A prefix meaning one level of description higher. If X is some concept then **meta-X is data about, or processes operating on, X**.

  For example, a metasyntax is syntax for specifying syntax, metalanguage is a language used to discuss language, meta-data is data about data, and meta-reasoning is reasoning about reasoning.

- Source: The Free On-line Dictionary of Computing, © 1993-2004 Denis Howe

“Meta:”

- A prefix meaning one level of description higher. If X is some concept then **meta-X is data about, or processes operating on, X**.

  For example, a metasyntax is syntax for specifying syntax, metalanguage is a language used to discuss language, meta-data is data about data, and meta-reasoning is reasoning about reasoning.

This is difficult to explain briefly, but much hacker humour turns on deliberate confusion between meta-levels.

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Metaprogram: Our Definition

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- Code that explicitly manipulates or generates program elements such as:
  - Functions
  - Types
  - Classes
  - Variables
  - Constants
  - etc.

Metaprogram: Our Definition

- Code that explicitly manipulates or generates program elements such as:
  - Functions
  - Types
  - Classes
  - Variables
  - Constants
  - etc.
- For example?

Basic Concepts

- Domain: Parsing/translation
- Domain Abstractions: terminals, nonterminals, parse rules, semantic actions
- Domain Language:
  - Syntax (Yacc input syntax + `C' fragments)
  - Semantics (The generated parser)
- Metaprogram Data: Yacc's internal representation of those abstractions

Parsing Domain Language

expression ➔ term

expression ➔ expression '+' term

expression ➔ expression '–' term

term ➔ factor

| term '*' factor

| term '/' factor

factor ➔ INTEGER

| group

group ➔ '(' expression ')'

Parsing Domain Language

expression ➔ term

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| term '*' factor

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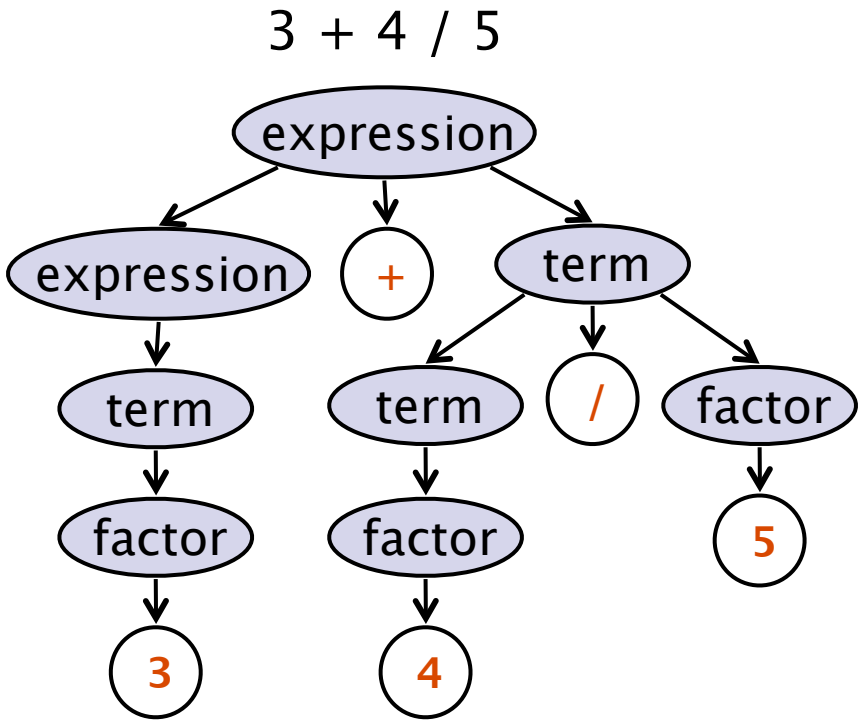
group ➔ '(' expression ')'



YACC Domain Language

```
expression : term
   | expression '+' term     { $$ = $1 + $3; }
   | expression '-' term     { $$ = $1 - $3; };

term : factor
   | term '*' factor         { $$ = $1 * $3; }
   | term '/' factor           { $$ = $1 / $3; };

factor : INTEGER
   | group;

group : '(' expression ')';
```

YACC Target Language (C)

```
const short yylhs[] = {
   -1,
    2,   0,   0,   3,   3,   4,   5,   5,
    5,   1,
    1,   1,
};
const short yylen[] = {
    2,
    0,   4,   0,   1,   1,   3,   1,   3,
    3,   1,
    3,   3,
};
const short yydefred[] = { ... };
const short yydgoto[] = { ... };
const short yysindex[] = { ... };
const short yyrindex[] = { ... };
const short yygindex[] = { ... };
```

```
yym = yylen[yyn];
yyval = yyvsp[1-yym];
switch (yyn)
{
case 1:
{ std::printf("= %d\n", yyvsp[0]); std::fflush
  (stdout); }
break;
case 8:
{ yyval = yyvsp[-2] * yyvsp[0]; }
break;
case 9:
{ yyval = yyvsp[-2] / yyvsp[0]; }
break;
case 11:
{ yyval = yyvsp[-2] + yyvsp[0]; }
break;
case 12:
{ yyval = yyvsp[-2] - yyvsp[0]; }
break;
}
yyssp -= yym;
...
```

Template Metaprogramming

- No Target Language
- Data: potential template arguments
- Domain Languages: subsets of native C++
- Downside: users constrained by C++ syntax
- Upside:
  - No hard boundary between metaprograms and "ordinary code"
  - Single Translation Step
  - Deep manipulation of native program elements.

Embedded Metaprogramming

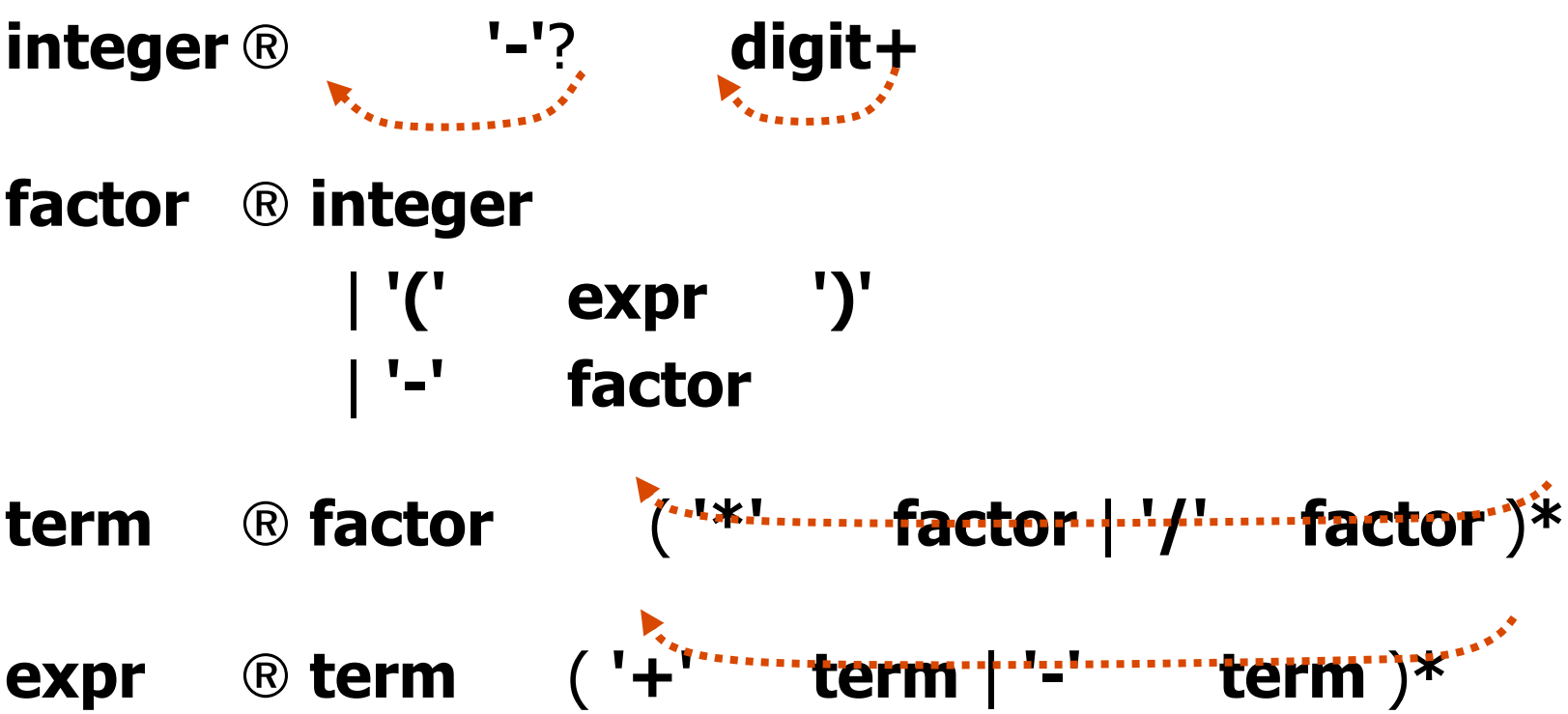
```
integer ® '-'? digit+

factor  ® integer
        | '(' expr ')'
        | '-' factor

term    ® factor ( '*' factor | '/' factor )*

expr    ® term ( '+' term | '-' term )*
```

Embedded Metaprogramming



Embedded Metaprogramming

```
spirit::rule<> expr, term, factor, integer;

integer = !ch_lit('-')  >> +digit;

factor  =  integer
         | '(' >>  expr >> ')'
         | '-' >>  factor;

term    =  factor >> *( '*' >>  factor | '/' >> factor );

expr    =  term >>  *( '+' >> term | '-' >>  term );
```

Compile-Time Computation

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
```

Compile-Time Computation

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template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
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struct binary<0>
{
    static unsigned const value
      = 0;
```

Compile-Time Computation

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template <unsigned long N>
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{
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    = N%10
      + 2 * binary<N/10>::value;
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struct binary<0>
{
    static unsigned const value
      = 0;
};
```

Compile-Time Computation

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```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

binary<1101>::value =

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

binary<1101>::value =

1 + 2 * binary<110>::value

binary<110>::value =

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
binary<1101>::value =
        1 + 2 * binary<110>::value
binary<110>::value =
         0 + 2 * binary<11>::value
binary<11>::value =
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
binary<1101>::value =
        1 + 2 * binary<110>::value
binary<110>::value =
         0 + 2 * binary<11>::value
binary<11>::value =
           1 + 2 * binary<1>::value
binary<11>::value =
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
binary<1101>::value =
        1 + 2 * binary<110>::value
binary<110>::value =
         0 + 2 * binary<11>::value
binary<11>::value =
           1 + 2 * binary<1>::value
binary<11>::value =
           1 + 2 * binary<0>::value
binary<0>::value
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
binary<1101>::value =
        1 + 2 * binary<110>::value = 13
binary<110>::value =
         0 + 2 * binary<11>::value
binary<11>::value =
           1 + 2 * binary<1>::value
binary<11>::value =
           1 + 2 * binary<0>::value
binary<0>::value
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
          1 + 2 * binary<110>::value
binary<110>::value =
           0 + 2 * binary<11>::value = 6
binary<11>::value =
             1 + 2 * binary<1>::value = 3
binary<11>::value =
             1 + 2 * binary<0>::value = 1
binary<0>::value                      = 0
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
            0 + 2 * binary<11>::value
binary<11>::value =
              1 + 2 * binary<1>::value = 3
binary<11>::value =
              1 + 2 * binary<0>::value = 1
binary<0>::value                       = 0
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

```
                1 + 2 * binary<1>::value
binary<11>::value =
                1 + 2 * binary<0>::value = 1
binary<0>::value                         = 0
```

Compile-Time Computation

binary<1101>::value ➔ 13

```
template <unsigned long N>
struct binary
{
  static unsigned const value
    = N%10
      + 2 * binary<N/10>::value;
};

template <>
struct binary<0>
{
    static unsigned const value
      = 0;
};
```

Why Metaprogramming?

- Why not runtime computation?

```
int binary(unsigned long n)

{
    return n ? n%10 + binary(n/10) * 2 : 0;
}
```

  - Metaprogram is faster at runtime (duh)
  - Metaprogram interacts deeply with host language
- Why not user analysis?

```
long odd_bits = binary<1010101>::value;

long even_bits = 0xAA;
```

  - Metaprogram is more convenient
  - Metaprogram is more reliable
  - Metaprogram brings us closer to the domain abstraction

It Takes Some Effort

Metaprogramming is for Lovers

It Takes Some Effort

Metaprogramming is Library Authors

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The Boost Metaprogramming Library: A Whirlwind Tour

Aleksey Gurtovoy (in the hat)

Why a TMP Library?

- Simplify complicated template system
- Hide low-level hacks
- Smooth over implementation differences
- Readability: reduce the syntactic burden
- Conceptual integrity: like STL, the concepts and idioms shape the way we program.
- Fun: high-level programming is more productive than using template "assembly language"

MPL Metafunction Concept

- A class template
- Operating on types only
- Single return "value" (i.e. a type)
- Called ::type

```
template <class A1, class A2, ...An>
struct identifier
{
    typedef type-expression type;
};
```

- If ::value appears, it's purely optional.

Metadata Polymorphism?

```
template <class T>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <int N>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <void(&f)(long)>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                    // class template
```

Metadata Polymorphism?

```
template <void(*pf)(long)>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <int& rx>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <int* px>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <int (pair<int,int>::*pm)>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism?

```
template <template <class,class> class C>
struct foo {};


int obj;
void f(long);


foo<char*>                          // OK
foo<1>                                 // integral constant
foo<f>                              // function reference
foo<&f>                             // function pointer
foo<obj>                         // object reference
foo<&obj>                        // object pointer
foo<&pair<int,int>::first>  // pointer to data member
foo<std::vector>                 // class template
```

Metadata Polymorphism

Solution: turn everything into a type with some kind of wrapper:

```
template <class T, T x>
struct wrap
{};
```

Works for almost everything…

```
wrap<int,5>                                   // OK

wrap<                                            // Also OK

        int std::pair<int,int>::*
      , &std::pair<int,int>::first >
{};
```

…except?

MPL Integral Constant

```
template <class T, T n>
struct integral_c
{
   typedef T value_type;
   static T const value = n;

   typedef integral_c<T,n> type; // self
   operator T() const { return n; }
};

template <int n>
struct int_ : integral_c<int,n> {};

template <bool x>
struct bool_ : integral_c<bool,x> {};
   ...
```

Type Logic

```
typedef bool_<true> true_;
typedef bool_<false> false_;


template <
    class C, class T, class F
>
struct if_;
```

Type Logic

```
typedef bool_<true> true_;
typedef bool_<false> false_;


template <
    class C, class T, class F
>
struct if_;
```

```
template <class T, class F>
struct if_<true_,T,F>
{
    typedef T type;
};

template <class T, class F>
struct if_<false_,T,F>
{
    typedef F type;
};
```

Type Sequences

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()

typedef mpl::at<v1, mpl::int_<2> >::type
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()

typedef mpl::at<v1, mpl::int_<2> >::type
  four_chars;
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()

typedef mpl::at<v1, mpl::int_<2> >::type
  four_chars;
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()

typedef mpl::at<v1, mpl::int_<2> >::type
  four_chars;

typedef mpl::list<int*, long, char[4]> l1;
```

Type Sequences

```
typedef mpl::vector<int*,long,char[4]> v1;


typedef mpl::deref<
    mpl::begin<v1>::type      // MPL iterators
>::type pointer_to_int;     // *v1.begin()

typedef mpl::at<v1, mpl::int_<2> >::type
  four_chars;

typedef mpl::list<int*, long, char[4]> l1;
```

Algorithms

Algorithms

```
template<class Iter, class T>                                   // STL
void replace(Iter first, Iter last, T const& old, T const& new);


template<class Sequence, class OldType, class NewType...> // MPL
```

Algorithms

```
template<class Iter, class T>                                   // STL
void replace(Iter first, Iter last, T const& old, T const& new);


template<class Sequence, class OldType, class NewType...> // MPL
struct replace;


template<class InIter, class OutIter, class UnaryOp>       // STL
OutIter transform(InIter first, InIter last, OutIter result, UnaryOp op);
```

Algorithms

```
template<class Iter, class T>                                   // STL
void replace(Iter first, Iter last, T const& old, T const& new);

template<class Sequence, class OldType, class NewType...> // MPL
struct replace;

template<class InIter, class OutIter, class UnaryOp>       // STL
OutIter transform(InIter first, InIter last, OutIter result, UnaryOp op);

template <class Sequence, class UnaryOp...>                     // MPL
struct transform;
```

Lazy Logic

```
struct dumb_add_ptr<class T>

{ typedef T* type; };

template <class T>

struct smart_add_ptr
  : mpl::if_<
          is_reference<T>
      , T
      , dumb_add_ptr<T>::type
> {};

typedef smart_add_ptr<int&>::type oops;
```

Lazy Logic

```
struct dumb_add_ptr<class T>

{ typedef T* type; };

template <class T>

struct smart_add_ptr
   : mpl::eval_if<
              is_reference<T>
           , mpl::identity<T>
           , dumb_add_ptr<T>
> {};

typedef smart_add_ptr<int&>::type oops; ok;
```

Views / Lazy Sequences

```
template <class Sequence, class UnaryOp>
struct transform_view;


template <class Sequence, class Predicate>
struct filter_view;


template <class SequenceOfSequences>
struct zip_view;


template <class T, T Start, T Finish>
```

Example: Dimensional

- Computation with units (typechecking for scientists)
- Newtons Law: $F = ma$
  - Breakdown:

$$a = \frac{\Delta v}{\Delta t}, \qquad v = \frac{\Delta l}{\Delta t}$$

  - Units of v: l / t e.g. miles per hour
  - Units of a: (l / t) / t = l / t^2 e.g. feet per sec. squared
  - Units of F: ml / t^2 e.g. kg m/s^2

The Challenge

- Addition/Subtraction
  boring – can't combine different units

  f(m + l); // error!

- Multiplication/Division

  interesting – produces new types

  f(m * l); // OK – a type representing ml

- Challenge: compute the new type

MPL Integral Sequence

- Convenient shorthand for type sequence of integral constant wrappers

mpl::**list_c**<int, i_1, i_2, ...i_n>

≈ mpl::list<
mpl::int_<i_1>, mpl::int_<i_1>
, ...mpl::int_<i_n>
>

Representing Units

```
typedef list_c<int,1,0,0,0,0,0,0> mass;
typedef list_c<int,0,1,0,0,0,0,0> length;
typedef list_c<int,0,0,1,0,0,0,0> time;
typedef list_c<int,0,0,0,1,0,0,0> charge;
typedef list_c<int,0,0,0,0,1,0,0> temperature;
typedef list_c<int,0,0,0,0,0,1,0> intensity;
typedef list_c<int,0,0,0,0,0,0,1>
   amount_of_substance;
typedef list_c<int,0,0,0,0,0,0,0,0> scalar; // e.g. pi
typedef list_c<int,0,1,-2,0,0,0,0> acceleration;
```

Representing Quantities

- Bind metadata to a runtime value

```
template <class T, class Units>
class quantity
{
 public:
    explicit quantity(T x)
          : m_value(x) {}

    T value() const
       { return m_value; }

 private:
    T m_value;
};

quantity<float, time> t(99.7);
```

Addition/Subtraction

- Just combine "like quantities"

```
template <class T, class U>
quantity<T,U>
operator+(quantity<T,U> x, quantity<T,U> y)
{
    return quantity<T,U>(x.value() + y.value());
}

template <class T, class U>
quantity<T,U>
operator-(quantity<T,U> x, quantity<T,U> y)
{
    return quantity<T,U>(x.value() - y.value());
}
```

Multiplication/Division

- Must compute return units

```
template <class T, class U1, class U2>
quantity<T, ?? >
operator*( quantity<T,U1> x, quantity<T,U2> y );

template <class T, class U1, class U2>
quantity<T, ?? >
operator/( quantity<T,U1> x, quantity<T,U2> y );
```

- Add/subtract corresponding powers:

$$a = v/t = (l/t)/t$$

$$= l^{1} \cdot t^{-1} \cdot t^{-1} = l^{1} \cdot t^{-2}$$

Multiplication/Division

- Use MPL's transform algorithm:

```
template <class Seq1, class Seq2, class BinaryOp>
struct transform;          → Result Sequence
```

- Similar to STL transform:

```
template <
   class InIter1, class InIter2,
   class OutIter, class BinaryOp
>
void transform(
   InIter1 start1, InIter1 finish1, InIter2 start2
  , OutIter, BinaryOp
)
```

What is the BinaryOp?

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- MPL gives us plus/minus

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```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
```

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```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>
```

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>
```

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
```

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<-1>
```

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
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```

What is the BinaryOp?

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mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
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➔ mpl::int_<-1>
```

- Are we done now?

What is the BinaryOp?

- MPL gives us plus/minus

  mpl::**plus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<5>

  mpl::**minus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<-1>

- Are we done now?

  template <class T, class U1, class U2>

ERROR

What is the BinaryOp?

- MPL gives us plus/minus

  mpl::**plus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<5>

  mpl::**minus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<-1>

- Are we done now?

  template <class T, class U1, class U2>
  quantity<

What is the BinaryOp?

- MPL gives us plus/minus

  mpl::**plus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<5>

  mpl::**minus**<mpl::int_<2>, mpl::int_<3> >::type
  ➔ mpl::int_<-1>

- Are we done now?

  template <class T, class U1, class U2>
  quantity<
  T

ERROR

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<-1>
```

- Are we done now?

```
template <class T, class U1, class U2>
quantity<
    T
  , typename mpl::transform<U1,U2,mpl::plus>::type
```

ERROR

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<-1>
```

- Are we done now?

```
template <class T, class U1, class U2>
quantity<
    T
  , typename mpl::transform<U1,U2,mpl::plus>::type
>
```

ERROR

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<-1>
```

- Are we done now?

```
template <class T, class U1, class U2>
quantity<
    T
  , typename mpl::transform<U1,U2,mpl::plus>::type
>
operator*(quantity<T,U1> x, quantity<T,U2> y);
```

ERROR

What is the BinaryOp?

- MPL gives us plus/minus

```
mpl::plus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<5>

mpl::minus<mpl::int_<2>, mpl::int_<3> >::type
➔ mpl::int_<-1>
```

- Are we done now?

```
template <class T, class U1, class U2>
quantity<
    T
  , typename mpl::transform<U1,U2,mpl::plus>::type
>
operator*(quantity<T,U1> x, quantity<T,U2> y);
```

ERROR

- Templates are not polymorphic metadata (types)!

Metafunction Classes

- Applying familiar type-wrapper idiom:

```
struct plus_f

{
  template <class T1, class T2>          // nested metafunction
  struct apply
  {
    typedef typename mpl::plus<T1,T2>::type type;
  };
};
```

```
template <class T, class U1, class U2>
quantity<
    T, typename mpl::transform<U1,U2,plus_f>::type  // OK
>
operator*(quantity<T,U1> x, quantity<T,U2> y);
```

- Definition: MPL Metafunction Class

  a class with a nested metafunction named "apply"

Division – 3 Simplifications

Division – 3 Simplifications

- #1: "Metafunction Forwarding"

```
struct minus_f
{
    template <class T1, class T2>
    struct apply : mpl::minus<T1,T2> {};
};
```

Division – 3 Simplifications

- #1: "Metafunction Forwarding"

```
struct minus_f
{
    template <class T1, class T2>
    struct apply : mpl::minus<T1,T2> {};
};
```

- Replaces

  typedef typename … **::type type;**

  with:

  :

Division – 3 Simplifications

- #1: "Metafunction Forwarding"

```
struct minus_f
{
    template <class T1, class T2>
    struct apply : mpl::minus<T1,T2> {};
};
```

- Replaces

  typedef typename … **::type type;**

  with:

  :

- Powerful syntactic trick; use it often…

Division – 3 Simplifications

- #1: "Metafunction Forwarding"

```
struct minus_f
{
    template <class T1, class T2>
    struct apply : mpl::minus<T1,T2> {};
};
```

- Replaces

  typedef typename … **::type type;**

  with:

  :

- Powerful syntactic trick; use it often…

  but wrapping metafunctions still boring (no fun)

Simplification #2:

```
template <class T, class U1, class U2>
quantity<
      T
  , typename mpl::transform<
          U1,U2,mpl::minus<_1,_2>
       >::type
>
operator/(quantity<T,U1> x, quantity<T,U2> y)
{
    return quantity<
        T
          , typename mpl::transform<
              U1,U2,mpl::minus<_1,_2>
            >::type
    >(
      x.value() / y.value()
    );
}
```

- Not boring! Fun!

Simplification #3: Refactoring

```
template <class U1, class U2>

divide_units
  : mpl::transform<U1,U2,mpl::minus<_1,_2> >
{};


template <class T, class U1, class U2>
quantity<T, typename divide_units<U1,U2>::type>
operator/(quantity<T,U1> x, quantity<T,U2> y)
{
    return quantity<
            T, typename divide_units<U1,U2>::type
      >(
             x.value() / y.value()
       );
}
```

Higher-Order (Meta)

- Functions which operate on or return other functions, e.g. transform

- "Higher-order functional programming"
  - Fancy title for a simple concept
    …but well-earned!

- Possible because metafunctions are polymorphic

Writing a Higher-Order Metafunction

- The Task:

$$\text{twice}(f,x) \quad := \quad f(f(x))$$

- Implementation for metafunction class F:

```
template <class F, class X>
struct twice
{
 private:
    typedef typename F::template apply<X>::type once;
 public:
    typedef
      typename F::template apply<once>::type
    type;
};
```

Writing a Higher-Order Metafunction

- Simplified using forwarding:

```
template <class F, class X>
struct twice
    : F::template apply<
            typename F::template apply<X>::type
      >
{};
```

- Refactored:

```
template <class UnaryMFC, class Arg>
struct apply1
  : UnaryMFC::template apply<Arg>
{};


template <class F, class X>
struct twice
  : apply1<F, typename apply1<F,X>::type>
{};
```

Handling Placeholders

Handling Placeholders

- Add a number to itself **twice**

```
template <class X>
struct times4
  : twice< mpl::plus<_1,_1>, X > {};
typedef times4<int_<4> >::type sixteen; // error!
```

Handling Placeholders

- Add a number to itself **twice**

```
template <class X>
struct times4
  : twice< mpl::plus<_1,_1>, X > {};
typedef times4<int_<4> >::type sixteen; // error!
```

- Why doesn't it work?

```
template <class T1, class T2>
struct plus
{
    typedef ... type;
};
```

Handling Placeholders

- Add a number to itself **twice**

```
template <class X>
struct times4
  : twice< mpl::plus<_1,_1>, X > {};
typedef times4<int_<4> >::type sixteen; // error!
```

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template <class T1, class T2>
struct plus
{
    typedef ... type;
};
```

Handling Placeholders

- Add a number to itself **twice**

```
template <class X>
struct times4
  : twice< mpl::plus<_1,_1>, X > {};
typedef times4<int_<4> >::type sixteen; // error!
```

- Why doesn't it work?

```
template <class T1, class T2>
struct plus
{
    typedef ... type;
};
```

- No nested apply<…> – not a metafunction class

The Lambda Metafunction

- **plus<_1,_1>** is called a "lambda expression"
- lambda<*lambda-expr*>::type ➔ Metafunction Class

```
template <class X>
struct times4
  : twice<
        typename mpl::lambda<
                    mpl::plus<_1,_1>
                >::type, X
      >
{};
```

- Note: lambda<…> passes metafunction classes through untouched

The Lambda Calculus

- Branch of mathematical logic
- Deals with the application of functions to their arguments
- Developed in the late ’30s and early ’40s, by…

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- Branch of mathematical logic
- Deals with the application of functions to their arguments
- Developed in the late ’30s and early ’40s, by…

Alonzo Church

Internal Lambda

- MPL algorithms apply lambda so you don't have to
- MPL's flexible version of **apply1**:

```
template <class UnaryOp, class Arg>
struct apply1
    : lambda<UnaryOp>::type
        ::template apply<Arg>
{};
```

- mpl::**apply**<F, A1, A2, …A*n*> is the *n*-ary version
- To handle both lambda expressions and metafunction classes as arguments, invoke them with **apply***N* or **apply**

The Power of Lambda

- Transform binary → unary metafunction

```
mpl::plus<_1,_1>
```

- Also via currying (arg. binding)

```
mpl::plus<_1, mpl::int_<42> >
```

- Functional Composition:

```
mpl::times<
   mpl::plus<_1,_2>
 , mpl::minus<_1,_2>
>
```

BOOST
CONSULTING

Boost Metaprogramming Concepts & Frameworks

Building a Domain-Specific Embedded Language (DSEL)

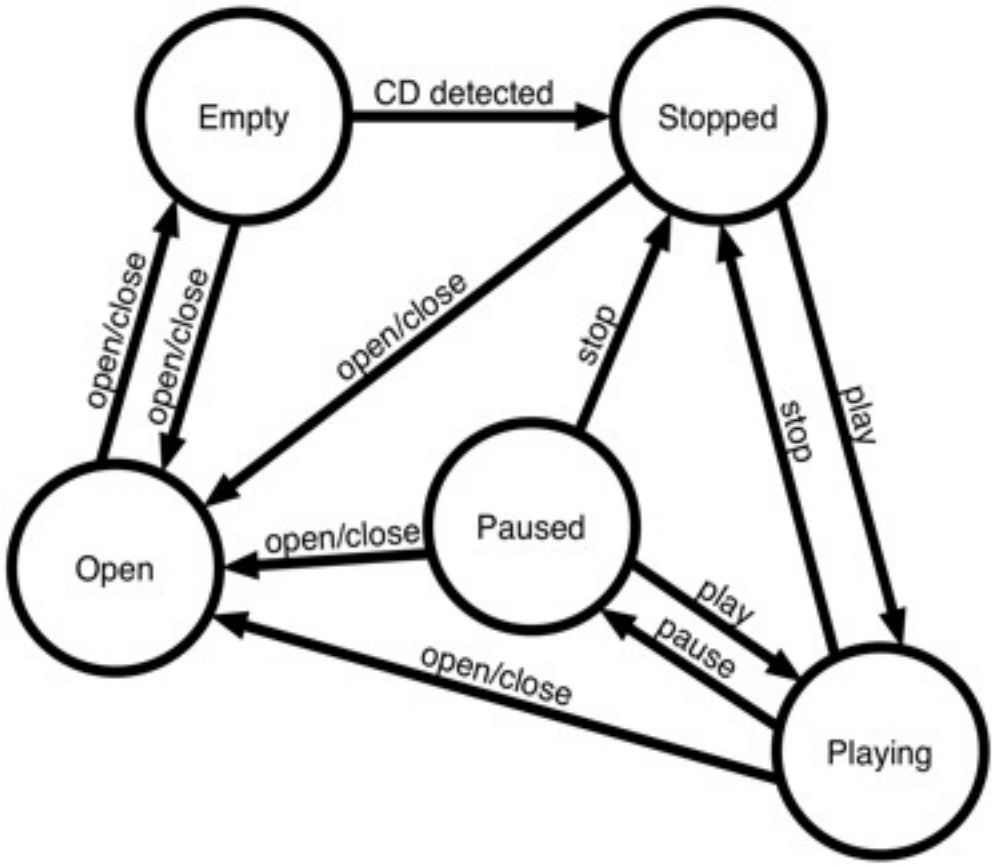
Finite State Machines (FSMs)

- Uses:
  - Embedded system controllers
  - Parsing (YACC parsers are stacks of FSMs)
  - Pattern Matching
  - Hardware Verification
  - Natural Language Processing
  - Any other stateful process
- Not Turing Complete
- Maybe that's a good thing?

1) Understand Domain Abstraction

- **States** e.g. locked, unlocked, ready
- **Transitions** define legal paths from state to state, often with an associated **action**.
- **Events** trigger transitions, e.g. coin-inserted, tokens (in a parser). May be internally-generated.

2) Review Standard Notations



Simple CD Player

State Transition Table (STT)

Current State	Event	Next State	Transition Action
Stopped	*play*	*Playing*	start playback
Stopped	*open/close*	*Open*	open drawer
Open	*open/close*	*Empty*	close drawer; collect CD information
Empty	*open/close*	*Open*	open drawer
Empty	*cd detected*	*Stopped*	store CD information
Playing	*stop*	*Stopped*	stop playback
Playing	*pause*	*Paused*	pause playback
Playing	*open/close*	*Open*	stop playback; open drawer
Paused	*play*	*Playing*	resume playback
Paused	*stop*	*Stopped*	stop playback
Paused	*open/close*	*Open*	stop playback; open drawer

3) Choose an Embedded Notation

3) Choose an Embedded Notation

```
      // start     event       finish       action
fsm  [ stopped,  play,        playing,     start_playback    ]
     [ playing,   pause,         paused,     pause_playback  ]...

fsm  [ stopped   |   play      |   playing  |   start_playback    ]
     [ playing   |   pause     |   paused     |   pause_playback  ]...

fsm=    +---------+-------------+---------+---------------
    +
     ! stopped | on<play>()   | playing | start_playback |
     +---------+-------------+---------+----------------+
     ! playing | on<pause>()  | paused  | pause_playback |
     +---------+-------------+---------+----------------+
     ...end;

 //  +---------+-------+---------+--------------------+
row<  stopped , play  , playing , &p::start_playback  >,
 //  +---------+-------+---------+--------------------+
row<  playing , pause , paused  , &p::pause_playback  >
 //  +---------+-------+---------+--------------------+
```

4) Consider Usage of Product

```
int main()
{
    player p;                  // FSM object

    p.process_event(drawer()); // user opens CD player
    p.process_event(drawer()); // inserts CD and closes


    p.process_event(                    // CD is detected
       cd_detected(
           "louie, louie"
        , std::vector<std::clock_t>( ...track lengths... )
       )
    );
```

Nail Down Representation of Events

```
struct play {};
struct open_close {};
struct pause {};

struct cd_detected
{
    cd_detected(
      std::string name,
      std::vector<std::clock_t> const& track_lengths
        )
            : name(name), track_lengths(track_lengths)
      {}

    std::string name;
```

FSM Declaration

```
class player          // Curiously Recurring Template Pattern
  : public state_machine<player>
{
    friend class state_machine<player>;
    enum states { Empty, Open, Stopped, Playing, Paused,
                  initial_state = Empty };


    void start_playback(play const&);      // transition actions
    void open_drawer(drawer const&);
    void close_drawer(drawer const&);
    void store_cd_info(cd_detected const&);
    void stop_playback(stop const&);
    void pause_playback(pause const&);
    void resume_playback(play const&);
    void stop_and_open(drawer const&);
```

FSM and its use (whole enchilada)

```
class player : public state_machine<player>    // player.hpp
{
 private:
    // the list of FSM states
    enum states {
        Empty, Open, Stopped, Playing, Paused
      , initial_state = Empty
    };

    void start_playback(play const&);
    void open_drawer(open_close const&);
    void close_drawer(open_close const&);
    void store_cd_info(cd_detected const&);
    void stop_playback(stop const&);
    void pause_playback(pause const&);
    void resume_playback(play const&);
    void stop_and_open(open_close const&);


    friend class state_machine<player>;
    typedef player p; // makes transition table cleaner

    // transition table
    struct transition_table : mpl::vector11<

    //    Start     Event         Next      Action
    //  +---------+-------------+---------+---------------------+
    row < Stopped , play        , Playing , &p::start_playback  >,
```

```
// player.cpp

void player::start_playback(play const&){}
void player::open_drawer(open_close const&){}
void player::close_drawer(open_close const&){}
void player::store_cd_info(cd_detected const&){}
void player::stop_playback(stop const&){}
void player::pause_playback(pause const&){}
void player::resume_playback(play const&){}
void player::stop_and_open(open_close const&){}


// main.cpp

int main()
{
    player p;

    p.process_event(open_close()); // user opens CD player
    p.process_event(open_close()); // inserts CD and closes
    p.process_event(               // CD is detected
        cd_detected(
          "louie, louie"
        , std::vector<std::clock_t>( /* track lengths */ )
        )
    );
    p.process_event(play());       // etc.
    p.process_event(pause());
    p.process_event(play());
    p.process_event(stop());
    return 0;
}
```

5) Implementing the

- i.e., we need to define the state_machine<…> class template
- Note that the definition of our FSM, player, contains **no details** about how the state machine is implemented
- We can choose among various implementation strategies.

Curiously Recurring Template Pattern

```
};
```

Curiously Recurring Template Pattern

```
                class FSM,

};
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <



        };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {




      };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;



      };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;
        typedef Event event;



      };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;
        typedef Event event;
        typedef FSM fsm_t;


      };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;
        typedef Event event;
        typedef FSM fsm_t;


      };
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;
        typedef Event event;
        typedef FSM fsm_t;

      };static void execute(FSM& fsm, Event const& e)
```

Curiously Recurring Template Pattern

```
template <class FSM>
struct state_machine
{
    template <
        int FromState, class Event, int ToState
      , void (FSM::*action)(Event const&) >
    struct row
    {
        static int const from_state = FromState;
        static int const to_state = ToState;
        typedef Event event;
        typedef FSM fsm_t;

      };static void execute(FSM& fsm, Event const& e)
        { (fsm.*action)(e); }
```

Dispatching Events (By Hand)

```
template <class FSM>
void state_machine<FSM>::process_event(play const& e)
{
   switch (this->state)
    {
     case Stopped:
      this->start_playback(e);
      this->m_state = playing;
      break;
     case Paused:
      this->resume_playback(e);
      this->m_state = playing;
      break;
     default:
      this->no_transition(e);
```

Breakdown for Code

Breakdown for Code

```
void process_event(play const& e)
{
  this->state = case_Stopped(e);
}


int case_Stopped(play const& e)
{
  if (this->state == Stopped)
  {
    this->start_playback(e);
    return Playing;
  }
  else
  {
    return this->case_Paused(e);
  }
}
```

Breakdown for Code

```
void process_event(play const& e)
{
  this->state = case_Stopped(e);
}


int case_Stopped(play const& e)
{
  if (this->state == Stopped)
  {
    this->start_playback(e);
    return Playing;
  }
  else
  {
    return this->case_Paused(e);
  }
}
```

```
int case_default(play const& e)
{
  return this->no_transition(
    this->state, e);
}

int case_Paused(play const& e)
{
  if (this->state == Paused)
  {
    this->resume_playback(e);
    return Playing;
  }
```

Breakdown for Code

```
void process_event(play const& e)
{
  this->state = case_Stopped(e);
}


int case_Stopped(play const& e)
{
  if (this->state == Stopped)
  {
    this->start_playback(e);
    return Playing;
  }
  else
  {
    return this->case_Paused(e);
  }
}
```

```
int case_default(play const& e)
{
  return this->no_transition(
    this->state, e);
}

int case_Paused(play const& e)
{
  if (this->state == Paused)
  {
    this->resume_playback(e);
    return Playing;
  }
  else
  {
    return this->case_default(e);
```

Generating the Dispatch

```
int
case_Stopped(play const& e)
{
  if (this->state == Stopped)
  {
    this->start_playback(e);
    return Playing;
  }
  else
  {
    return
          this->case_Paused(e);
  }
}
```

Generating the Dispatch

```
int
case_Stopped(play const& e)
{
  if (this->state == Stopped)
  {
    this->start_playback(e);
    return Playing;
  }
  else
  {
    return
          this->case_Paused(e);
  }
}
```

```
template <int State, class E>
int case_(E const& e)
{
   if (fsm.state == State)
   {
     this->??????(e);
     return ?????;
   }
   else
   {
     return
          this->case_<???>(e);
   }
}
```

Generating the Dispatch

```
template<class   Row>
struct event_dispatcher
{
  typedef typename Row::fsm_t fsm_t;
  typedef typename Row::event event;

  static int dispatch(fsm_t& fsm, int state, event const& e)
  {
    if (state == Row::from_state)
    {
      Row::execute(fsm, e);
      return Row::to_state;
    }          ????;
    else
```

Generating the Dispatch

```
template<class   Row, class Next>
struct event_dispatcher
{
  typedef typename Row::fsm_t fsm_t;
  typedef typename Row::event event;

  static int dispatch(fsm_t& fsm, int state, event const& e)
  {
    if (state == Row::from_state)
    {
      Row::execute(fsm, e);
      return Row::to_state;
    }          ????;
    else
```

Generating the Dispatch

```
template<class   Row, class Next>
struct event_dispatcher
{
  typedef typename Row::fsm_t fsm_t;
  typedef typename Row::event event;

  static int dispatch(fsm_t& fsm, int state, event const& e)
  {
    if (state == Row::from_state)
    {
      Row::execute(fsm, e);
      return Row::to_state;
    }          Next::dispatch(fsm, state, e);
    else
```

“No Transition” Handler

```
struct default_event_dispatcher
{
  template<class FSM, class Event>
  static int dispatch(FSM& m, int state, Event const& e)
  {
     return m.call_no_transition(state, e);
  }
};
template <class FSM>

class state_machine
{
  template <class Event>
  int call_no_transition(int state, Event const& e)
  {
```

Must Assemble This Dispatcher Type

```
typedef player p;

event_dispatcher<
  row<Stopped, play, Playing, &p::start_playback>,

  event_dispatcher<
    row<Paused, play, Playing, &p::resume_playback>,

    default_event_dispatcher
  >

>
```

Generating the Dispatcher

```
template <class Row, class Event>
struct has_event
  : boost::is_same<typename Row::event, Event>
{};


template<class RowSequence, class Event>
struct generate_dispatcher
  : mpl::accumulate<                    // a.k.a. fold
      // Select all rows with transitions on Event
      mpl::filter_view<RowSequence, has_event<_1,Event> >,
      // Terminating case
      default_event_dispatcher,
      // Accumulator
```

Finally, the Event Processor

```
template<class Event>
int process_event(Event const& event)
{
    typedef typename generate_dispatcher<
      typename FSM::transition_table, Event
    >::type dispatcher;


    this->state = dispatcher::dispatch(
        static_cast<FSM&>(*this),
        this->state,
        event
    );
```

Final Details of state_machine<>

```
public:
   template <class Event>
   int no_transition(int state, Event const& e)
   {
       assert(false);
       return state;
   }


protected:
   state_machine()
     : state(FSM::initial_state)
   {}
```

What Have We Achieved?

- As expressive as custom (text-based) state machine compiler
- Better scalability, maintainability, type safety, expressiveness, and efficiency than State pattern.
- Efficiency comparable to hand-coded FSM
- Fully Declarative: procedural logic fully replaceable

Boost Metaprogramming Concepts & Frameworks

Other Metaprogramming Paradigms in C++

Tuple – The Quantum

```
typedef boost::tuple<
    int, char const*, bool
> t;

t s(3, “hello”, true);
```

- heterogeneous sequence of values (wave):
  3, “hello”, true
- also a sequence of types (particle):
  int, char const*, bool

Fusion/MPL Interoperability

- Every fusion tuple is a valid MPL sequence
- fusion::as_vector(*mpl-sequence-type*()) ➔ tuple

Fusion: Tuple

- Primitives:
  - begin(s), end(s) ➔ iterators
  - next(p), prior(q) ➔ adjacent iterators
  - Some standard STL iterator operations:

    *p p == q p != q
- Algorithms:
  - for_each(s, unary_function) ➔ void
  - transform(s, unary_function) ➔ transform_view
  - push_back(s, value) ➔ ??
  - fold(s, init, binary_function) ➔ ??

Why Fusion Algorithms Yield Views

```
fusion::tuple<std::string, std::string>    x( “hello”, “world” );

fusion::for_each(
    fusion::push_back(
        fusion::push_back(
            fusion::push_back(x, 1)
          , std::vector<int>(5)
        )
      , 12
    )
   , some_function
);
```

Why Fusion Algorithms Yield Views

```
fusion::tuple<std::string, std::string>    x( “hello”, “world” );

fusion::for_each(
    fusion::push_back(
        fusion::push_back(
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← copy two strings?

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);
```

← copy two strings, one int?

Why Fusion Algorithms Yield Views

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fusion::tuple<std::string, std::string>    x( “hello”, “world” );

fusion::for_each(
    fusion::push_back(
        fusion::push_back(
            fusion::push_back(x, 1)
          , std::vector<int>(5)
        )
      , 12
    )
   , some_function
);
```

← copy two strings, one int, one vector?

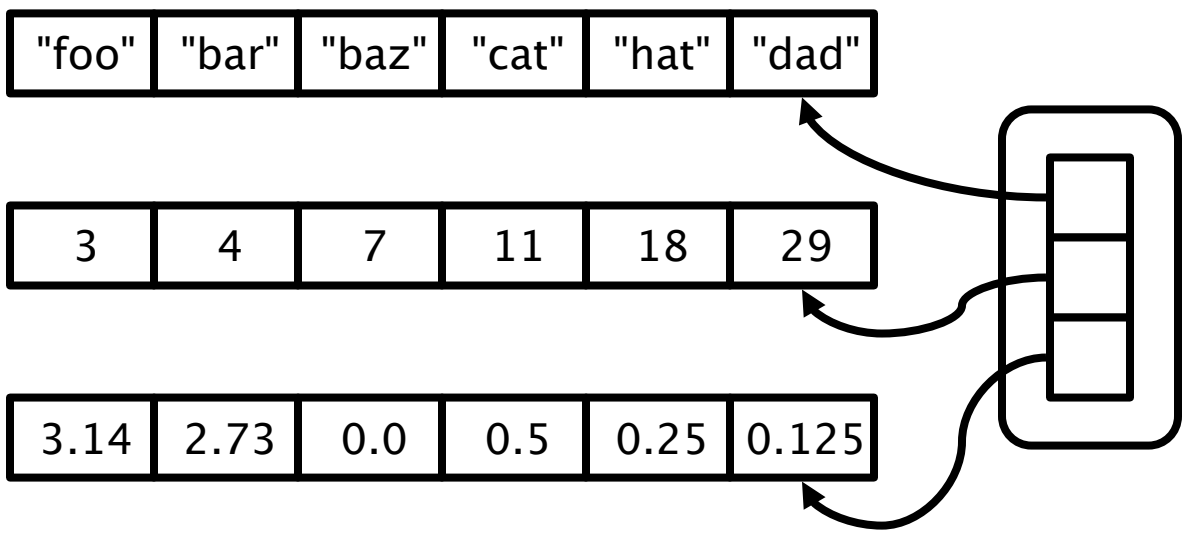
How to Get a Real Tuple

```
fusion::tuple<std::string, std::string>    x( “hello”,
   “world” );

fusion::as_vector(
    fusion::push_back(
        fusion::push_back(
            fusion::push_back(x, 1)
          , std::vector<int>(5)
        )
     , 12
    )
)
```

Example: zip_iterator<IterTuple>

- Stores a tuple of iterators into different sequences
- Traverses the sequences in parallel
- operator* yields a tuple of references



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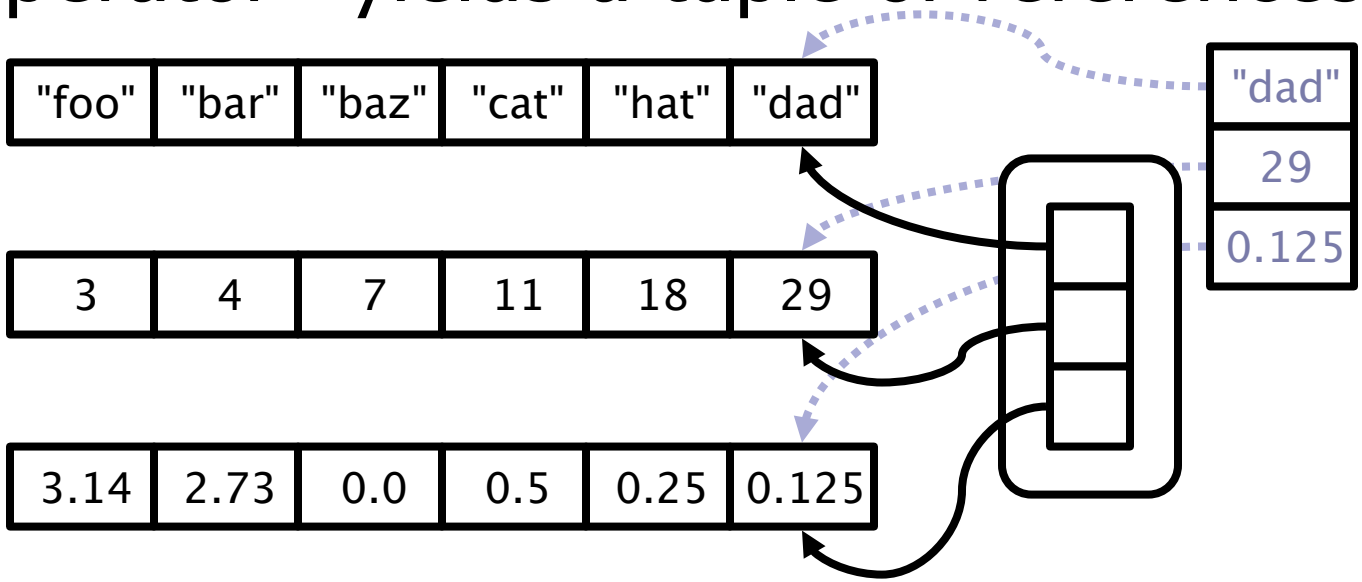

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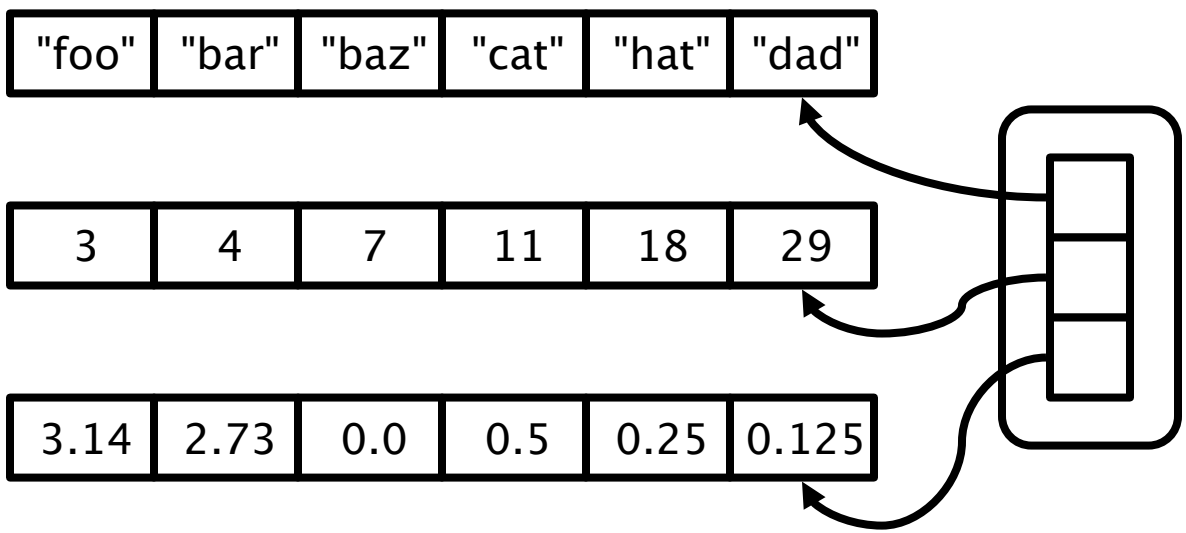

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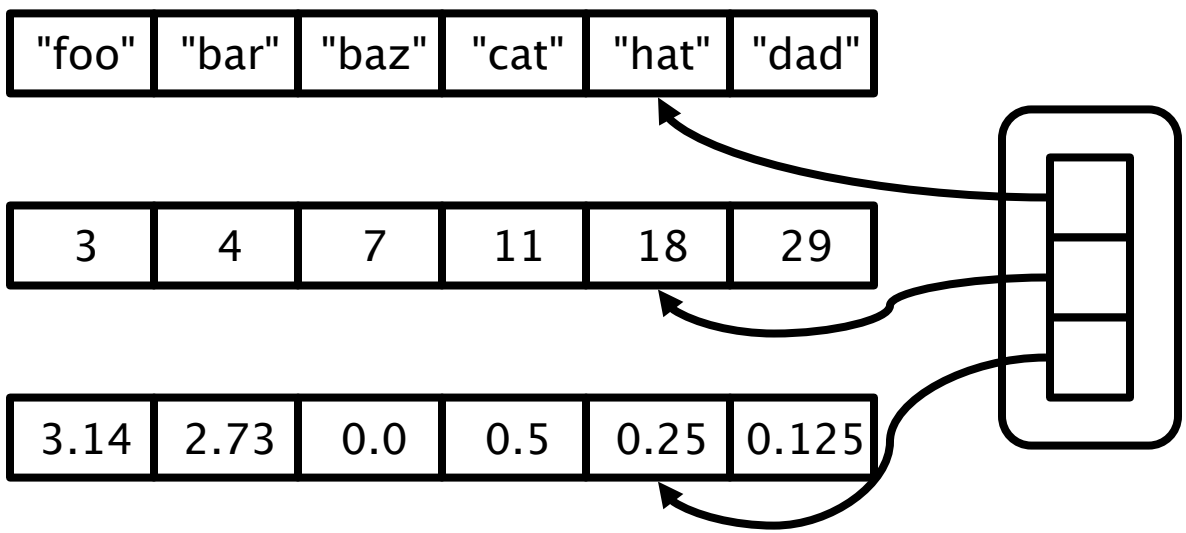

Why zip_iterator?

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Consider std::transform:

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```
std::transform(start, finish, result, op);
```

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Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, start8, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, start8, result, op);
```

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, start8, result, op);
```

At some point, you want to generalize back to:

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, start8, result, op);
```

At some point, you want to generalize back to:

Why zip_iterator?

Consider std::transform:

```
std::transform(start, finish, result, op);
std::transform(start, finish, start2, result, op);

std::transform(start, finish, start2, start3, result, op);
std::transform(start, finish, start2, start3, start4, result, op);
std::transform(start, finish, start2, start3, start4, start5, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, result, op);
std::transform(start, finish, start2, start3, start4, start5, start6, start7, start8, result, op);
```

At some point, you want to generalize back to:

```
std::transform(zip_start, zip_finish, result, op);
```

From zip_iterator's Implementation

```
struct increment
{
    template<typename T>
    void operator()(T& x) const
       { ++x; }
};


template <class IteratorTuple>
zip_iterator<IteratorTuple>::operator++()
{
    fusion::for_each(this->m_iterators, increment());
};
```

From zip_iterator's Implementation

From zip_iterator's Implementation

```
template <class IteratorTuple>
zip_iterator<IteratorTuple>::operator++()
{
    using namespace boost::lambda;
    fusion::for_each( this->m_iterators, ++_1 );
};
```

Implementing Dereference

```
struct deref
{
  // return type computation
  template<typename Iterator>
  struct result
  {
    typedef typename
    std::iterator_traits<
       Iterator
    >::reference  type;
  };


  // runtime function call
  template<typename Iter>
  typename result<Iter>::type
  operator()(Iter const& it)
  const
```

```
template <class IteratorTuple>
struct zip_iterator
{
  typedef typename
  mpl::transform<
      IteratorTuple
    , deref::apply<mpl::_1>
  >::type reference;

  reference operator*() const
  {
    return fusion::transform(
          this->m_iterators
      , deref()
    );
  }
     ...
     IteratorTuple m_iterators;
};
```

Fusion Tuple

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- Merges pure type manipulation and runtime computation

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Fusion Tuple

- Merges pure type manipulation and runtime computation
- Makes manipulation of heterogeneous collections easy
- Interoperates seamlessly with MPL
- A floor wax and a dessert topping.

Preprocessor

- The preprocessor is a text generator

  ```
  #define FOO(x)  foo x
  FOO(bar)    ➔    foo bar
  ```

- You can program it

- What if you use it to generate C++ program text?

Preprocessor Abstractions

- preprocessing token
- 2 kinds of macros
  - object-like: #define **X** y
  - function-like #define **FOO**(x) foo x
- macro argument
  - Sequence of preprocessing tokens
  - All parens are balanced
  - No commas outside of parens

Problem: Generate Overload

```
tuple<> make_tuple()
{ return tuple<>(); }

template <class A0>
tuple<A0> make_tuple(A0 x0)
{ return tuple<A0>(x0); }

template <class A0, class A1>
tuple<A0,A1> make_tuple(A0 x0, A1 x1)
{ return tuple<A0,A1>(x0,x1); }

template <class A0, class A1, class A3>
tuple<A0,A1> make_tuple(A0 x0, A1 x1, A3 x3)
{ return tuple<A0,A1,A3>(x0,x1,x3); }

template <class A0, class A1, class A3, class A4>
tuple<A0,A1> make_tuple(A0 x0, A1 x1, A3 x3, A4 x4)
{ return tuple<A0,A1,A3,A4>(x0,x1,x3,x4); }
```

Boost.Preprocessor Solution

```
tuple<> make_tuple()
{ return tuple<>(); }


#define FUSION_make_tuple(z, n, unused)                    \
template < BOOST_PP_ENUM_PARAMS(n, class A) >              \
tuple< BOOST_PP_ENUM_PARAMS(n, A) >                        \
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )        \
{                                                          \
    return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(            \
        BOOST_PP_ENUM_PARAMS(n, x)                         \
    );                                                     \
}

BOOST_PP_REPEAT_FROM_TO(
    1, FUSION_MAX_SIZE, FUSION_make_tuple, ~)
```

Boost.Preprocessor Solution

```
tuple<> make_tuple()
{ return tuple<>(); }


#define FUSION_make_tuple(z, n, unused)                          \
template < class A0, class A1, class A2, class A3 > \
tuple< BOOST_PP_ENUM_PARAMS(n, A) >                                  \
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )    \
{                                                                    \
    return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(          \
        BOOST_PP_ENUM_PARAMS(n, x)                                \
    );                                                               \
}

BOOST_PP_REPEAT_FROM_TO(
    1, FUSION_MAX_SIZE, FUSION_make_tuple, ~)
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Boost.Preprocessor Solution

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tuple<> make_tuple()
{ return tuple<>(); }


#define FUSION_make_tuple(z, n, unused)                          \
template < class A0, class A1, class A2, class A3 > \
tuple< A0, A1, A2, A3 >                                          \
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )    \
{                                                                    \
    return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(          \
        BOOST_PP_ENUM_PARAMS(n, x)                               \
    );                                                               \
}

BOOST_PP_REPEAT_FROM_TO(
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Boost.Preprocessor Solution

```
tuple<> make_tuple()
{ return tuple<>(); }


#define FUSION_make_tuple(z, n, unused)                          \
template < class A0, class A1, class A2, class A3 > \
tuple< A0, A1, A2, A3 >                                            \
make_tuple( A0 x0, A1 x1, A2 x2, A3 x3 )                         \
{                                                                          \
    return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(              \
        BOOST_PP_ENUM_PARAMS(n, x)                                \
    );                                                                    \
}

BOOST_PP_REPEAT_FROM_TO(
    1, FUSION_MAX_SIZE, FUSION_make_tuple, ~)
```

Boost.Preprocessor Solution

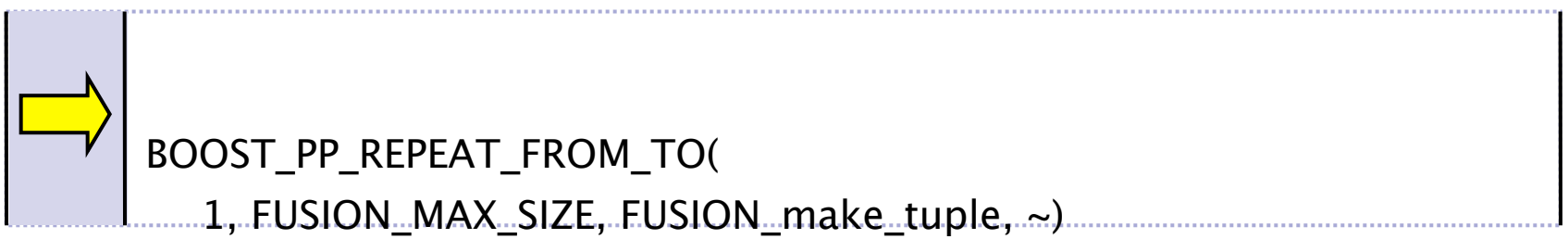
```
tuple<> make_tuple()
{ return tuple<>(); }


#define FUSION_make_tuple(z, n, unused)                          \
template < class A0, class A1, class A2, class A3 > \
tuple< A0, A1, A2, A3 >                                             \
make_tuple( A0 x0, A1 x1, A2 x2, A3 x3 )                         \
{                                                                                \
    return tuple< A0, A1, A2, A3 >(                                \
        x0, x1, x2, x3                                                  \
    );                                                                          \
}

BOOST_PP_REPEAT_FROM_TO(
    1, FUSION_MAX_SIZE, FUSION_make_tuple, ~)
```

What About Debuggability?

- A macro expansion never contains line breaks – "horizontal repetition"
- All make_tuple overloads ultimately generated by a single BOOST_PP_REPEAT
- Resulting code all generated on that line

```
template <class A0> tuple<A0> make_tuple(A0 x0) { return tuple<A0>(x0); } template <class A0, class A1> …
```

- Stepping through make_tuple in debugger



Vertical Repetition

```
#ifndef FUSION_MAKE_TUPLE_HPP        // #include guard
#  define FUSION_MAKE_TUPLE_HPP

tuple<> make_tuple() { return tuple<>(); }

#define BOOST_PP_ITERATION_LIMITS ( 1, FUSION_MAX_SIZE - 1)
#define BOOST_PP_FILENAME_1  "make_tuple_overload.hpp"
#include BOOST_PP_ITERATE()

#endif // FUSION_MAKE_TUPLE_HPP

// make_tuple_overload.hpp
#define n BOOST_PP_ITERATION()
template < BOOST_PP_ENUM_PARAMS(n, class A) >
tuple< BOOST_PP_ENUM_PARAMS(n, A) >
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )
{
   return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(
      BOOST_PP_ENUM_PARAMS(n, x) );
}
#undef n
```

Vertical Repetition

```
#ifndef FUSION_MAKE_TUPLE_HPP        // #include guard
#  define FUSION_MAKE_TUPLE_HPP

tuple<> make_tuple() { return tuple<>(); }

#define BOOST_PP_ITERATION_LIMITS ( 1, FUSION_MAX_SIZE - 1)
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tuple< BOOST_PP_ENUM_PARAMS(n, A) >
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )
{
    return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(
        BOOST_PP_ENUM_PARAMS(n, x) );
}
```
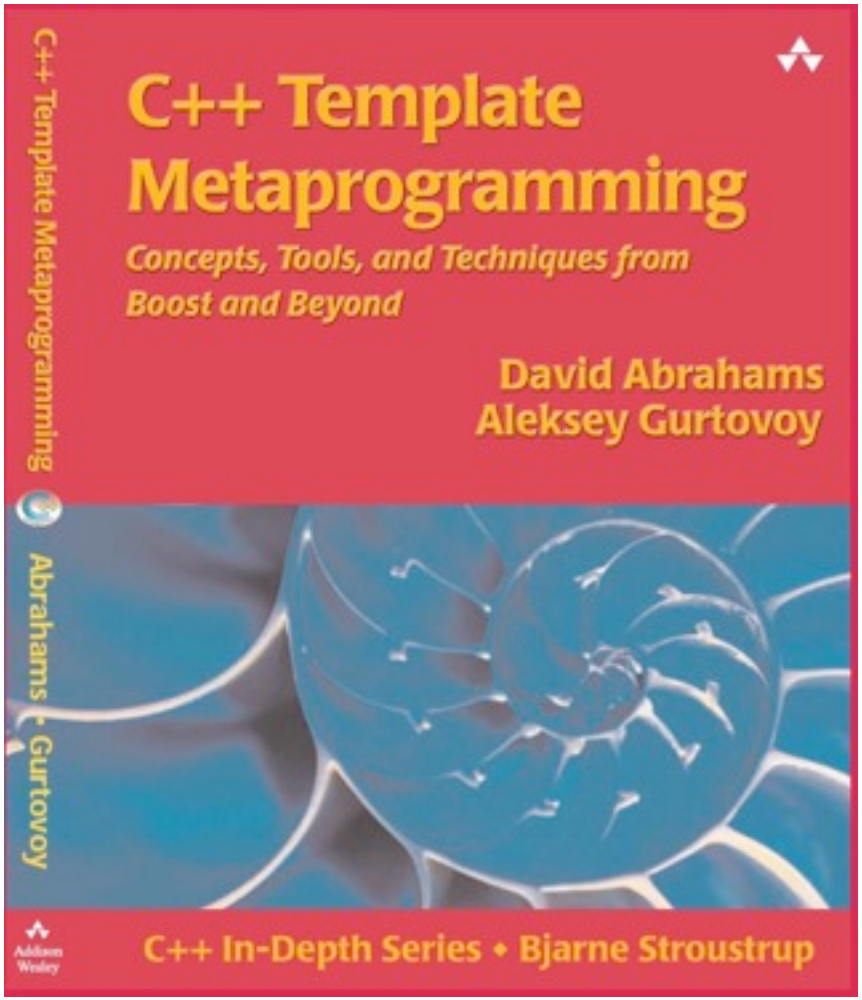

Self-Iteration

```
#ifndef BOOST_PP_IS_ITERATING
#  ifndef FUSION_MAKE_TUPLE_HPP

#    define FUSION_MAKE_TUPLE_HPP
tuple<> make_tuple() { return tuple<>(); }


#define BOOST_PP_ITERATION_LIMITS( 1, FUSION_MAX_SIZE - 1)
#define BOOST_PP_FILENAME_1  "make_tuple_overload.hpp"
#include BOOST_PP_ITERATE()
#  endif // FUSION_MAKE_TUPLE_HPP
#else

#  define n BOOST_PP_ITERATION()

template < BOOST_PP_ENUM_PARAMS(n, class A) >
tuple< BOOST_PP_ENUM_PARAMS(n, A) >
make_tuple( BOOST_PP_ENUM_BINARY_PARAMS(n, A, x ) )
{
   return tuple< BOOST_PP_ENUM_PARAMS(n, A) >(
      BOOST_PP_ENUM_PARAMS(n, x)
```

Other Boost.Preprocessor Facilities

- Sequences: (foo bar)(baz)(1 + 2)
- Sequence Algorithms:
  BOOST_PP_SEQ_FOR_EACH(f, data, seq)
  BOOST_PP_SEQ_FOLD_LEFT(f, data, seq)
- Token Arithmetic: **BOOST_PP_ADD**(3, 4) ➔ 7
- Token Logic: **BOOST_PP_AND**(1, 0) ➔ 0
- Like MPL, Boost.Preprocessor is a complete programming system.

Further Reading



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