Nested Lambda Expressions with Let expressions in C++ Template Metaprograms

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Outline

- Let expressions
- Template metaprogramming
- Let expressions in template metaprograms
- Lambda expressions
- Recursive let expressions

Let expressions

- Example
  - Restaurant
  - Happy Hours

Let expressions

```
burgerPrice hourOfDay =


    if hourOfDay < 20
      then 5
      else 4
```

Let expressions

```
burgerPrice hourOfDay =
  let
    happyHoursBegin = 20
    happyHoursPrice = 4
    normalPrice = 5
  in
    if hourOfDay < 20
      then 5
      else 4
```

Let expressions

```
burgerPrice hourOfDay =
  let
    happyHoursBegin = 20
    happyHoursPrice = 4
    normalPrice = 5
  in
    if hourOfDay < happyHoursBegin
      then normalPrice
      else happyHoursPrice
```

Let expressions

```
divMod a b = (a `div` b, a `mod` b)


-- divMod 7 3
-- (2, 1)


let
  (d, m) = divMod 7 3
in
  d * 3 + m
```

Let expressions

```
divMod(A, B) -> {A div B, A rem B}.


% divMod(7, 3).
% {2, 1}.


{D, M} = divMod(7, 3),
D * 3 + M.
```

C++ template metaprograms

- Code evaluated at compilation time
- Erwin Unruh, 1994.
- Strong connection with functional programming
- Library support: Boost metaprogramming library
- Turing-complete

C++ template metaprograms

```
template <class T>
struct makeConst
{
  typedef const T type;
};
```

Argument list

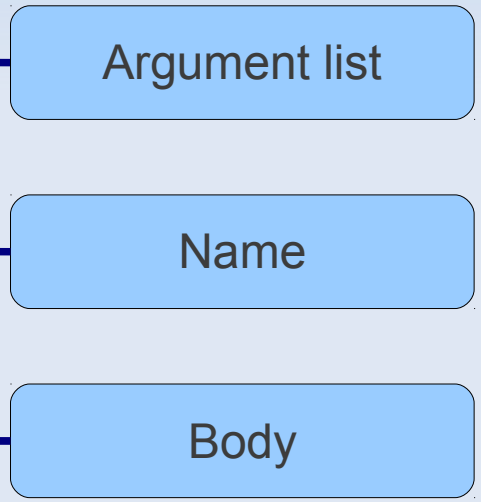
Name

Body

```
makeConst<int>::type
```

C++ template metaprograms

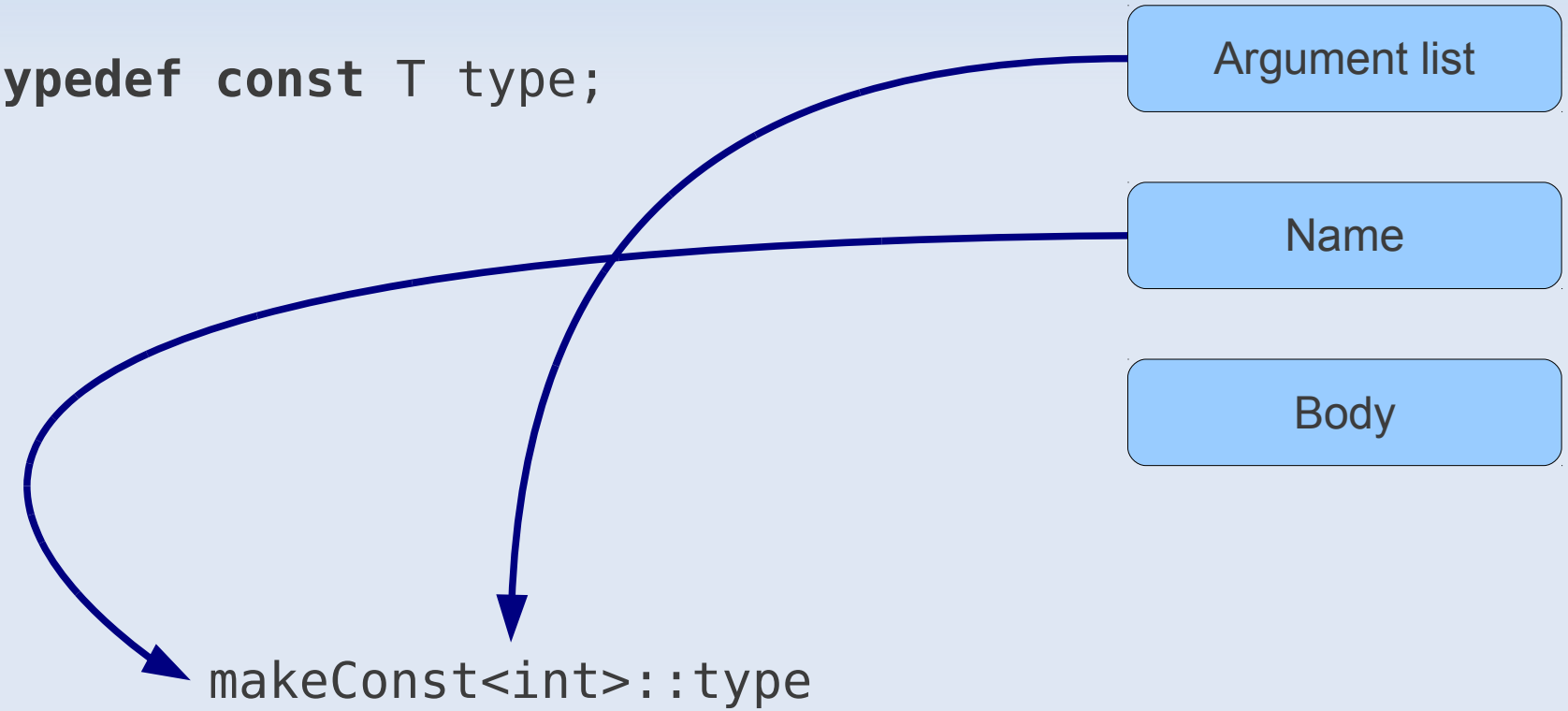
```
template <class T>
struct makeConst
{
  typedef const T type;
};
```




```
makeConst<int>::type
```

C++ template metaprograms

```
template <class T>
struct makeConst
{
  typedef const T type;
};
```



Template metafunction class

```
struct makeConst
{
   template <class T>
   struct apply
   {
      typedef const T type;
   };
};
```

Argument list

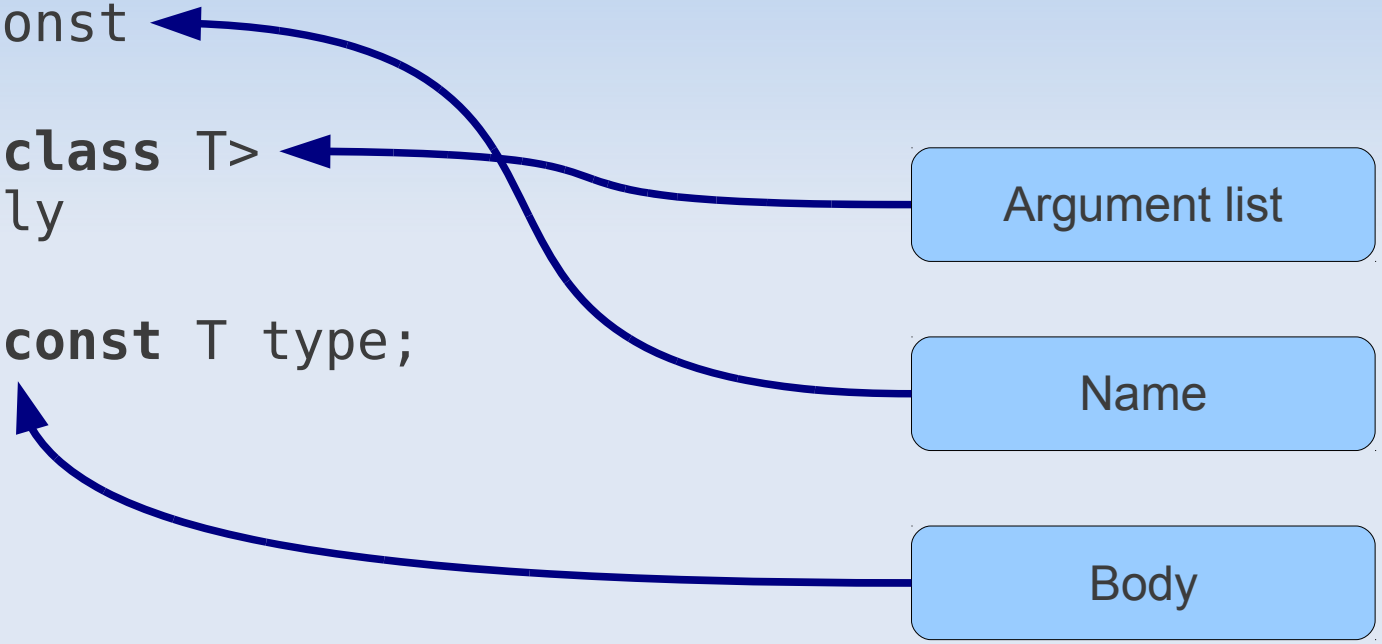
Name

Body

```
makeConst::apply<int>::type
```

Template metafunction class

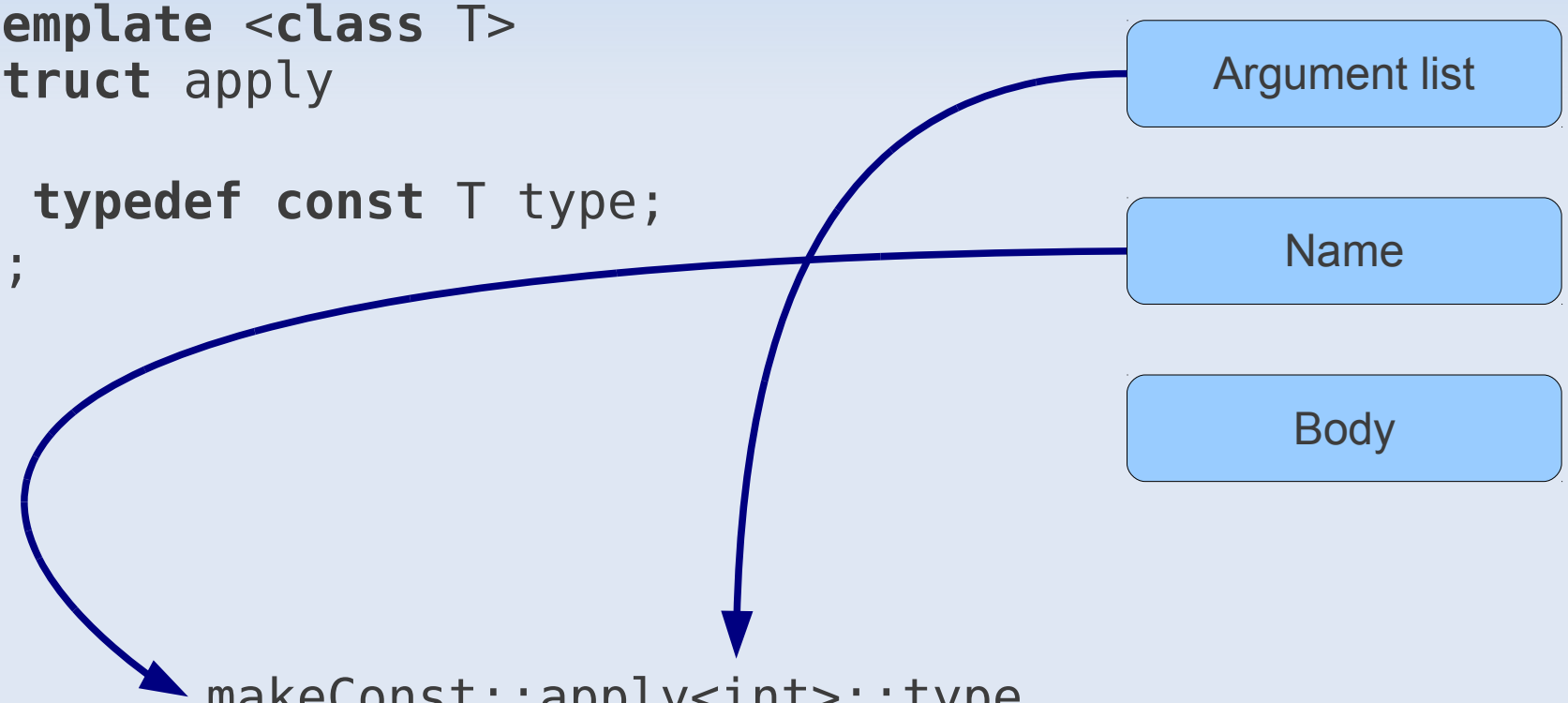
```
struct makeConst
{
  template <class T>
  struct apply
  {
    typedef const T type;
  };
};
```




```
makeConst::apply<int>::type
```

Template metafunction class

```
struct makeConst
{
   template <class T>
   struct apply
   {
      typedef const T type;
   };
};
```



Let expressions

```
burgerPrice hourOfDay =
  let
    happyHoursBegin = 20
    happyHoursPrice = 4
    normalPrice = 5
  in
    if hourOfDay < happyHoursBegin
      then normalPrice
      else happyHoursPrice
```

Let expressions

```
template <                    >
struct burgerPrice :




{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :




{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :



    boost::mpl::if_<


    >
{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :



    boost::mpl::if_<
      boost::mpl::less<hourOfDay,                    20  >,


    >

{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :



    boost::mpl::if_<
      boost::mpl::less<hourOfDay, boost::mpl::int_<20> >,


    >

{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :


    boost::mpl::if_<
      boost::mpl::less<hourOfDay, boost::mpl::int_<20> >,
      boost::mpl::int_<5>,
      boost::mpl::int_<4>
    >

{};
```

Let expressions

```
typedef boost::mpl::int_<20> happyHoursBegin;
typedef boost::mpl::int_<4> happyHoursPrice;
typedef boost::mpl::int_<5> normalPrice;

template <class hourOfDay>
struct burgerPrice :




    boost::mpl::if_<
      boost::mpl::less<hourOfDay, happyHoursBegin      >,
      normalPrice         ,
      happyHoursPrice
    >

{};
```

Let expressions

```
template <class hourOfDay>
struct burgerPrice :
  LET
    happyHoursBegin = boost::mpl::int_<20>,
    happyHoursPrice = boost::mpl::int_<4>,
    normalPrice = boost::mpl::int_<5>
  IN
    boost::mpl::if_<
      boost::mpl::less<hourOfDay, happyHoursBegin      >,
      normalPrice         ,
      happyHoursPrice
    >

{};
```

Let expressions

```
struct happyHoursBegin;
struct happyHoursPrice;
struct normalPrice;

template <class hourOfDay>
struct burgerPrice :
  let<
    happyHoursBegin,  boost::mpl::int_<20>,
    happyHoursPrice,  boost::mpl::int_<4>,
    normalPrice,  boost::mpl::int_<5>,

    boost::mpl::if_<
      boost::mpl::less<hourOfDay, happyHoursBegin      >,
      normalPrice         ,
      happyHoursPrice
    >
  >
{};
```

Nullary metafunctions

```
struct nullary_metafunction
{
  typedef int type;
};
```

Nullary metafunctions

```
struct nullary_metafunction
{
  typedef int type;
};

some_metafunction<int, double>
```

Nullary metafunctions

```
struct nullary_metafunction
{
  typedef int type;
};

some_metafunction<int, double>

nullary_metafunction::type
some_metafunction<int, double>::type
```

Let expressions

```
struct happyHoursBegin;
struct happyHoursPrice;
struct normalPrice;

template <class hourOfDay>
struct burgerPrice :
  let<
    happyHoursBegin,  boost::mpl::int_<20>,
    happyHoursPrice,  boost::mpl::int_<4>,
    normalPrice,  boost::mpl::int_<5>,
    boost::mpl::if_<
      boost::mpl::less<hourOfDay, happyHoursBegin      >,
      normalPrice          ,
      happyHoursPrice
    >
  >
{};
```

Nullary metafunction

Implementation of let

```
template <class name, class exp, class body>
struct let                                {};
```

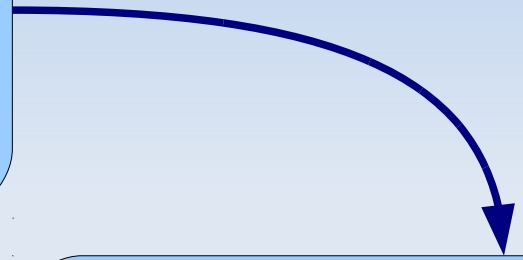
Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <class name, class exp, class body>
struct let                                {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```



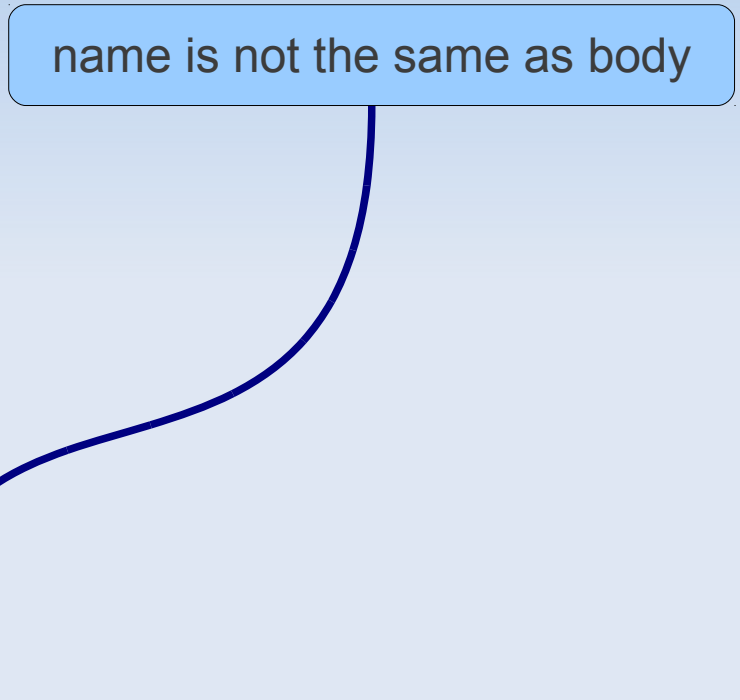
```
boost::mpl::plus<
  boost::mpl::int_<13>,
  boost::mpl::int_<13>
>
```

```
template <class name, class exp, class body>
struct let                                  {};
```

Implementation of let

```
template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let



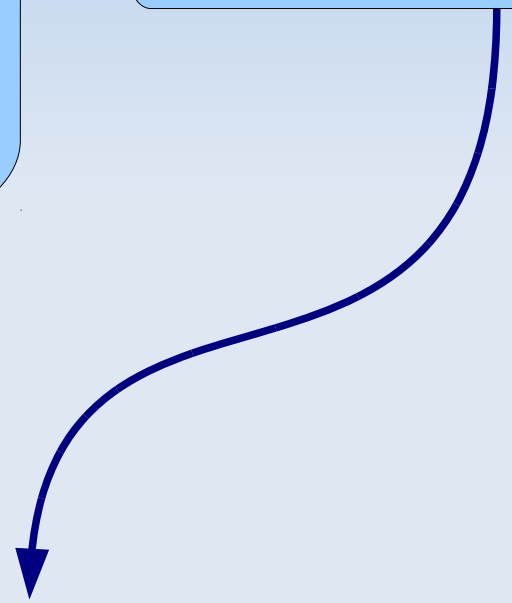

```
template <class name, class exp, class body>
struct let_impl                {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let_impl<
  x, boost::mpl::int_<13>,
  x
>
```

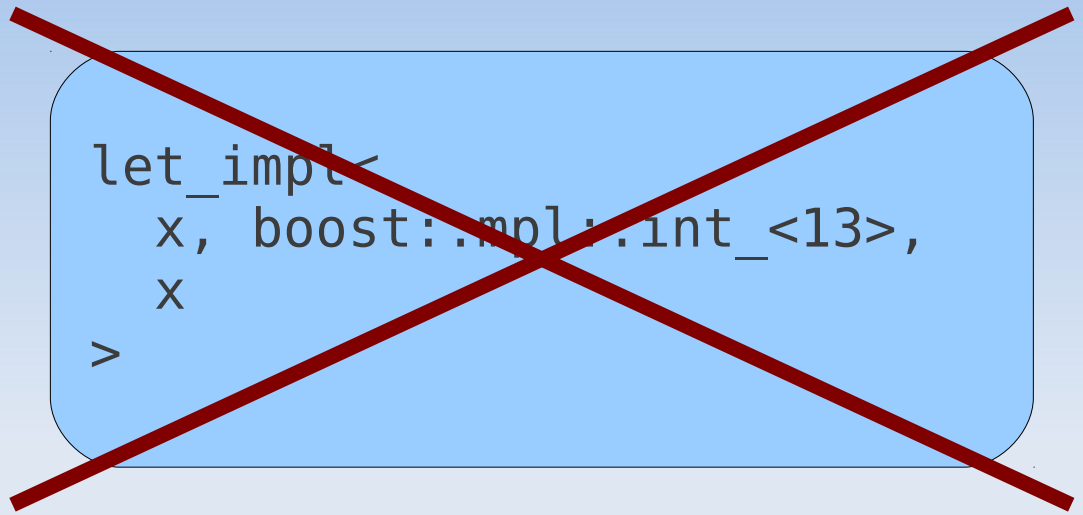
name is not the same as body



```
template <class name, class exp, class body>
struct let_impl                 {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let



name is not the same as body

```
template <class name, class exp, class body>
struct let_impl                 {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
template <class name, class exp, class body>
struct let_impl :    body  {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

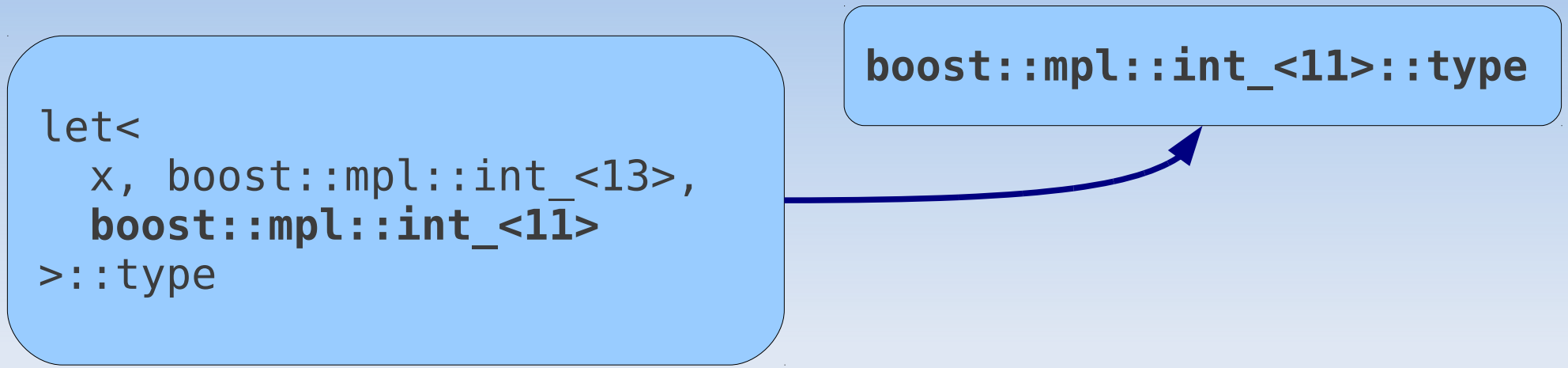
Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::int_<11>
>::type
```

```
template <class name, class exp, class body>
struct let_impl :    body  {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

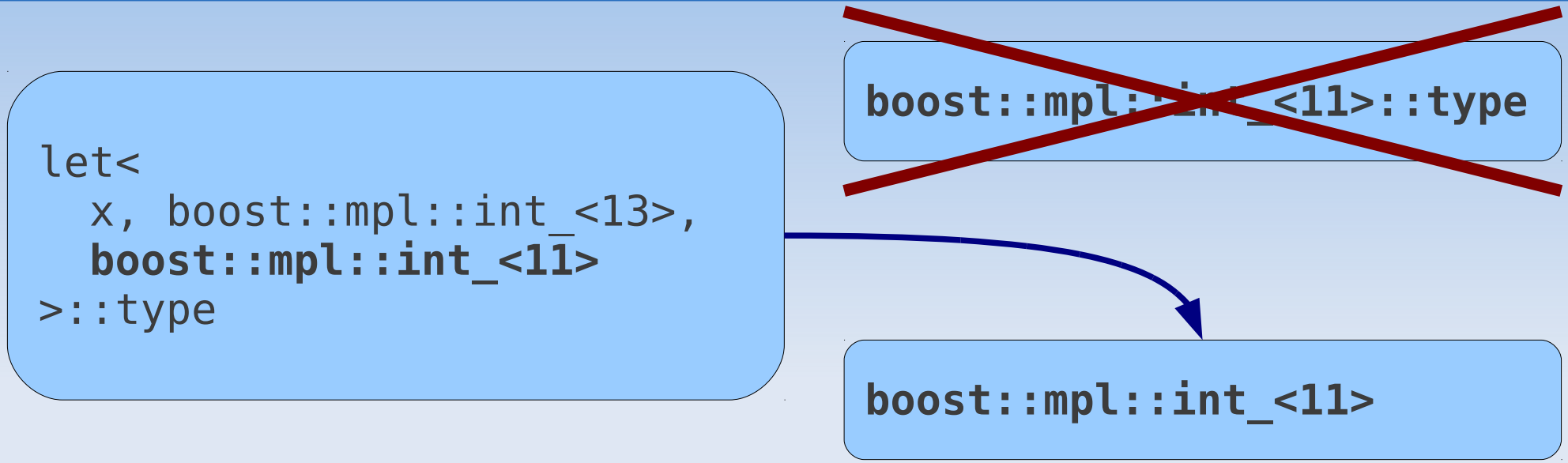
Implementation of let




```
template <class name, class exp, class body>
struct let_impl :    body  {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let




```
template <class name, class exp, class body>
struct let_impl :    body  {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
template <class name, class exp, class body>
struct let_impl : id<body> {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
template <class body>
struct id
{
  typedef body type;
};

template <class name, class exp, class body>
struct let_impl : id<body> {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
template <
  class name,
  class exp,
```

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
>
struct let_impl<name, exp,            > :
```

```
    {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <
  class name,
  class exp,
  template <class, class> class t,


>
struct let_impl<name, exp, t<       > > :


    {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <
  class name,
  class exp,
  template <class, class> class t,
  class a1,
  class a2
>
struct let_impl<name, exp, t<a1, a2> > :




    {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <
  class name,
  class exp,
  template <class, class> class t,
  class a1,
  class a2
>
struct let_impl<name, exp, t<a1, a2> > :
  id<
    t<
                                  a1       ,
                                  a2
    >
  > {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
let<
  x, boost::mpl::int_<13>,
  boost::mpl::plus<x, x>
>::type
```

```
template <
  class name,
  class exp,
  template <class, class> class t,
  class a1,
  class a2
>
struct let_impl<name, exp, t<a1, a2> > :
  id<
    t<
      typename let<name, exp, a1>::type,
      typename let<name, exp, a2>::type
    >
  > {};

template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Implementation of let

```
template <class name, class exp>
struct let<name, exp, name> : id<exp> {};
```

```
template <class name, class exp, class body>
struct let : let_impl<name, exp, body> {};
```

Name shadowing

```
let
  x = 11
in
  x + (let x = 13 in x + 11)
```

Name shadowing

```
let
  x = 11
in
  x + (let x = 13 in x + 11)
```

```
11 + (let x = 13 in x + 11)
```

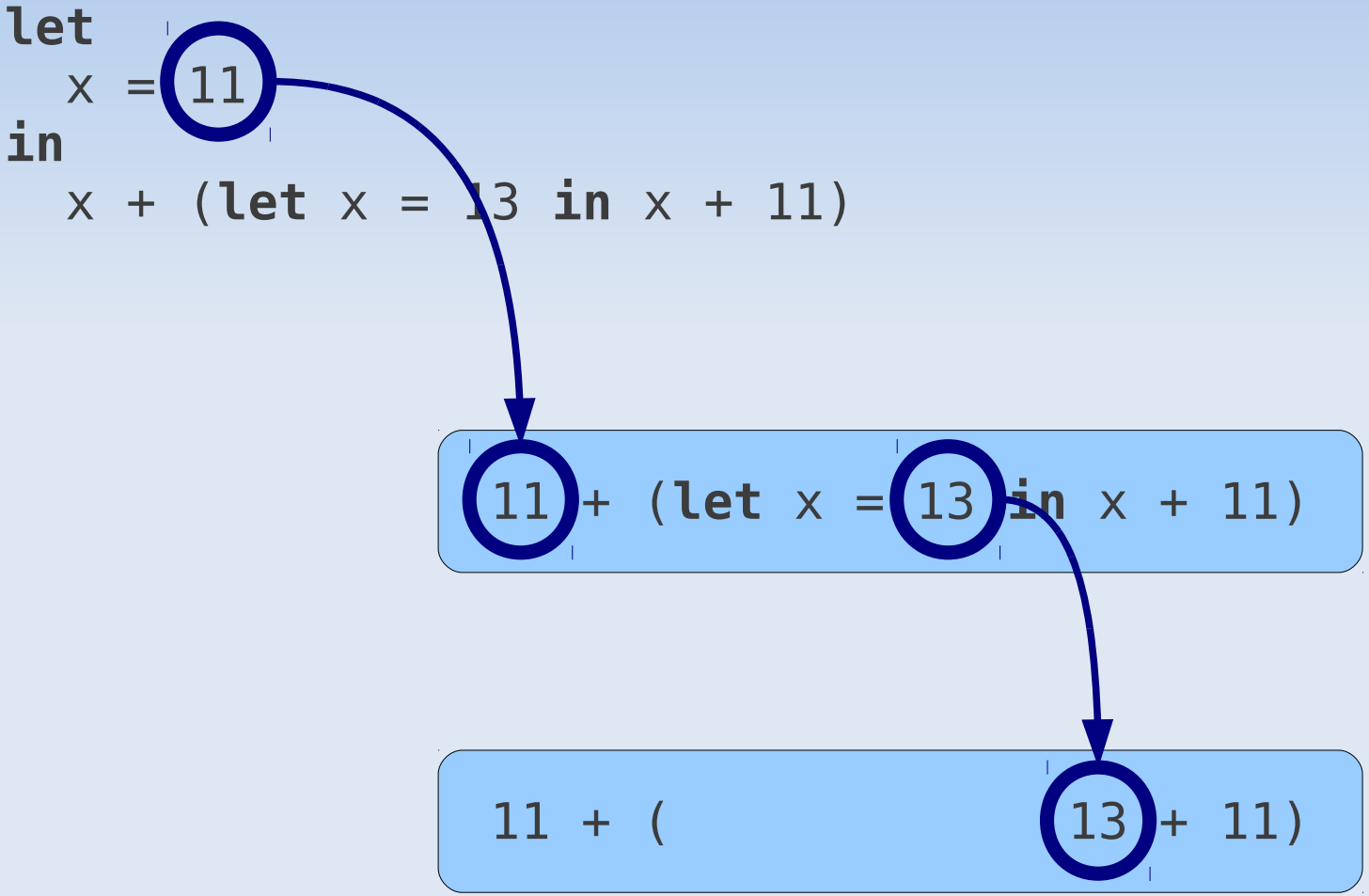
Name shadowing

```
let
  x = 11
in
  x + (let x = 13 in x + 11)
```

```
11 + (let x = 13 in x + 11)
```

```
11 + (                13 + 11)
```

Name shadowing



Name shadowing

```
let<
  x, int_<11>,

>
```

Name shadowing

```
let<
  x, int_<11>,
  plus<x,                                    >
>
```

Name shadowing

```
let<
  x, int_<11>,
  plus<x, let<x, int_<13>,                    > >
>
```

Name shadowing

```
let<
  x, int_<11>,
  plus<x, let<x, int_<13>, plus<x, int_<11> > > >
>
```

Name shadowing

```
let<
  x, int_<11>,
  plus<x, let<x, int_<13>, plus<x, int_<11> > > >
>
```

```
plus<
  int_<11>,
  let<int_<11>, int_<13>, plus<int_<11>, int_<11> > >
>
```

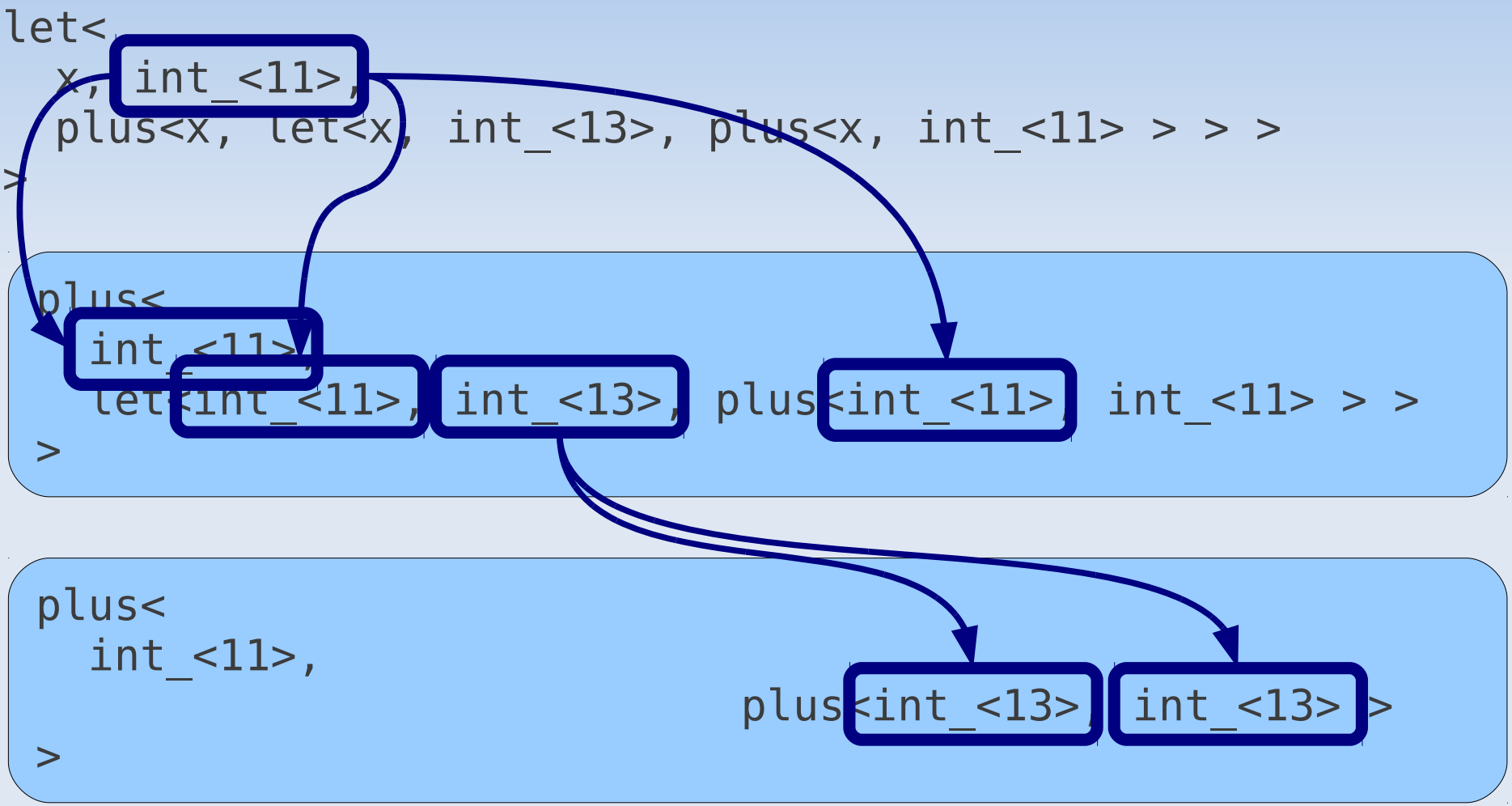
Name shadowing

```
let<
  x, int_<11>,
  plus<x, let<x, int_<13>, plus<x, int_<11> > > >
>
```

```
plus<
  int_<11>,
  let<int_<11>, int_<13>, plus<int_<11>, int_<11> > >
>
```

```
plus<
  int_<11>,
                          plus<int_<13>, int_<13> >
>
```

Name shadowing



Name shadowing

```
let<
  x, int_<11>,
  int_<11>,
                                  plus<int_<13>, int_<13>>
>
```

```
template <
  class name,
  class exp1,
  class exp2,
  class body
>
struct let_impl<name, exp1, let<name, exp2, body> > :
  id<let<name, exp2, body> >
{};
```

Let expressions

- Examples of let expressions
- Let expressions in C++ template metaprograms

```
let<
  x, boost::mpl::plus<a, b>,

  boost::mpl::mult<x, x>
>
```

Nested lambda expressions

- List of lists

```
[
  [          1, 2],
  [          3]
]
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

Nested lambda expressions

- List of lists

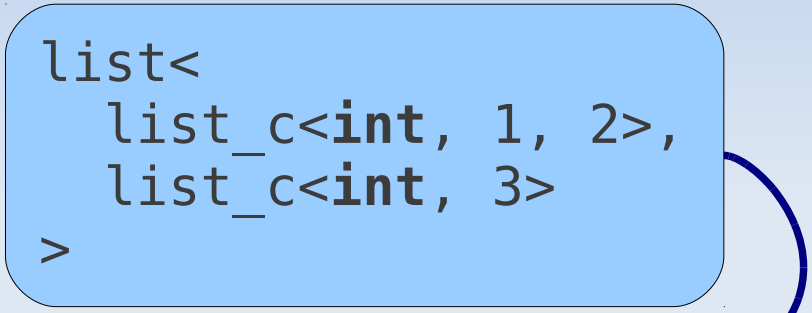
```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

- Add every element the length of the list it is in.

```
list<
  list_c<int, 3, 4>,
  list_c<int, 4>
>
```

Nested lambda expressions

- List of lists




```
transform<
  original_list_of_lists,
  lambda<




  >
>
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

```
transform<
  original_list_of_lists,
  lambda<
    transform<
      _1          ,
      lambda<


      >
    >
  >
>
```

Nested lambda expressions

- List of lists

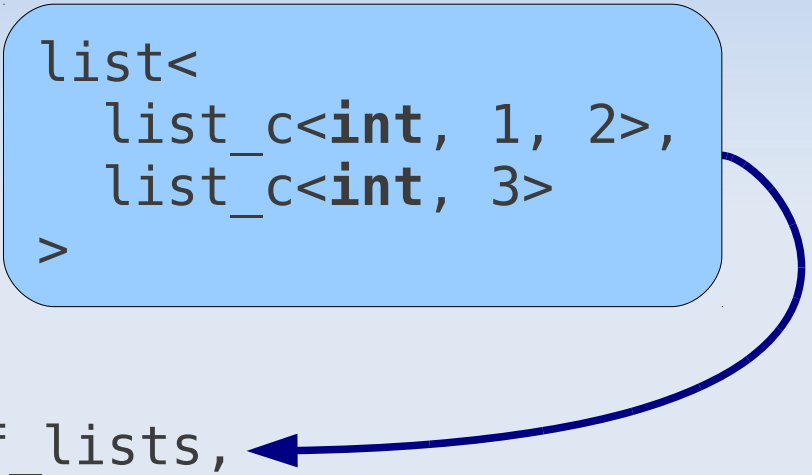
```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

```
transform<
  original_list_of_lists,
  lambda<
    transform<
      _1           ,
      lambda<
        plus<                 ,                    >
      >
    >
  >
>
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

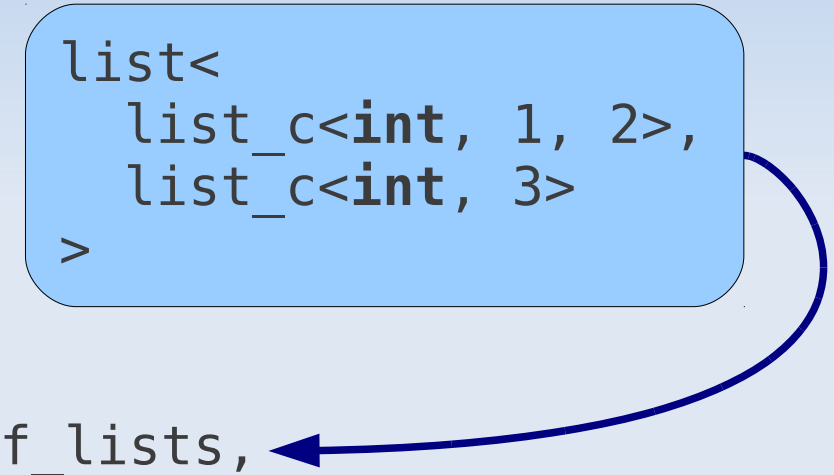


```
transform<
  original_list_of_lists,
  lambda<
    transform<
      _1           ,
      lambda<
        plus<_1          ,                    >
      >
    >
  >
>
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```



```
transform<
  original_list_of_lists,
  lambda<
    transform<
      _1           ,
      lambda<
        plus<_1          , size<            > >
      >
    >
  >
>
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

```
transform<
  original_list_of_lists,
  lambda<
    transform<
      _1           ,
      lambda<
        plus<_1          , size<          > >
      >
    >
  >
>
```

Nested lambda expressions

- List of lists

```
list<
  list_c<int, 1, 2>,
  list_c<int, 3>
>
```

```
transform<
  original_list_of_lists,
  our::lambda<current_list,
    transform<
      current_list,
      our::lambda<current_item,
        plus<current_item, size<current_list> >
      >
    >
  >
>
```

Building our lambda

```
template <class name, class body>
struct lambda
{


};
```

Building our lambda

```
template <class name, class body>
struct lambda
{
  template <class exp>
  struct apply :                                  {};
};
```

Building our lambda

```
template <class name, class body>
struct lambda
{
  template <class exp>
  struct apply : let<name, exp, body>::type {};
};
```

Let and lambda expressions

- Examples of let expressions
- Let expressions in C++ template metaprograms
- Nested lambda expressions

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda<




  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<



    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,


    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,

    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,
      times<                                  , n>
    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,
      times<apply<fact,                    >, n>
    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,
      times<apply<fact, minus< ,          > >, n>
    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,
      times<apply<fact, minus<n, int_<1> > >, n>
    >
  >,

>
```

Recursive let expressions

- Factorial

```
let<
  fact,
  lambda< n,
    lazy_eval_if<
      equal_to<n, int_<0> >,
      int_<1>,
      times<apply<fact, minus<n, int_<1> > >, n>
    >
  >,
  apply<fact, int_<3> >
>
```

Recursive let expressions

```
apply<


    fact,


  int_<3>
>
```

Recursive let expressions

```
apply<

    lambda< n,
      lazy_eval_if<
        equal_to<n, int_<0> >,
        int_<1>,
        times<apply<fact, minus<n, int_<1> > >, n>
      >
    >,

  int_<3>
>
```

Recursive let expressions

```
apply<
  let<
    fact,
    lambda< n,
      lazy_eval_if<
        equal_to<n, int_<0> >,
        int_<1>,
        times<apply<fact, minus<n, int_<1> > >, n>
      >
    >,
    lambda< n,
      lazy_eval_if<
        equal_to<n, int_<0> >,
        int_<1>,
        times<apply<fact, minus<n, int_<1> > >, n>
      >
    >
  >,
  int_<3>
>
```

Recursive let expressions

```
template <class name, class exp, class body>
struct letrec :

{};
```

Recursive let expressions

```
template <class name, class exp, class body>
struct letrec :
  let<name,                    exp , body>
{};
```

Recursive let expressions

```
template <class name, class exp, class body>
struct letrec :
  let<name, letrec<name, exp, exp>, body>
{};
```

Summary

- Let expressions are widely available
- Many functional programming languages support them
- No native support for it in C++ Template Metaprogramming
- It can be built as a library
- Using it, Boost MPL's lambda support can be improved

Q & A

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http://github.com/sabel83/mpllibs