Boost.Spirit V2.1

A Modern, Object oriented, Recursive-Descent Parser and Output Generation Library

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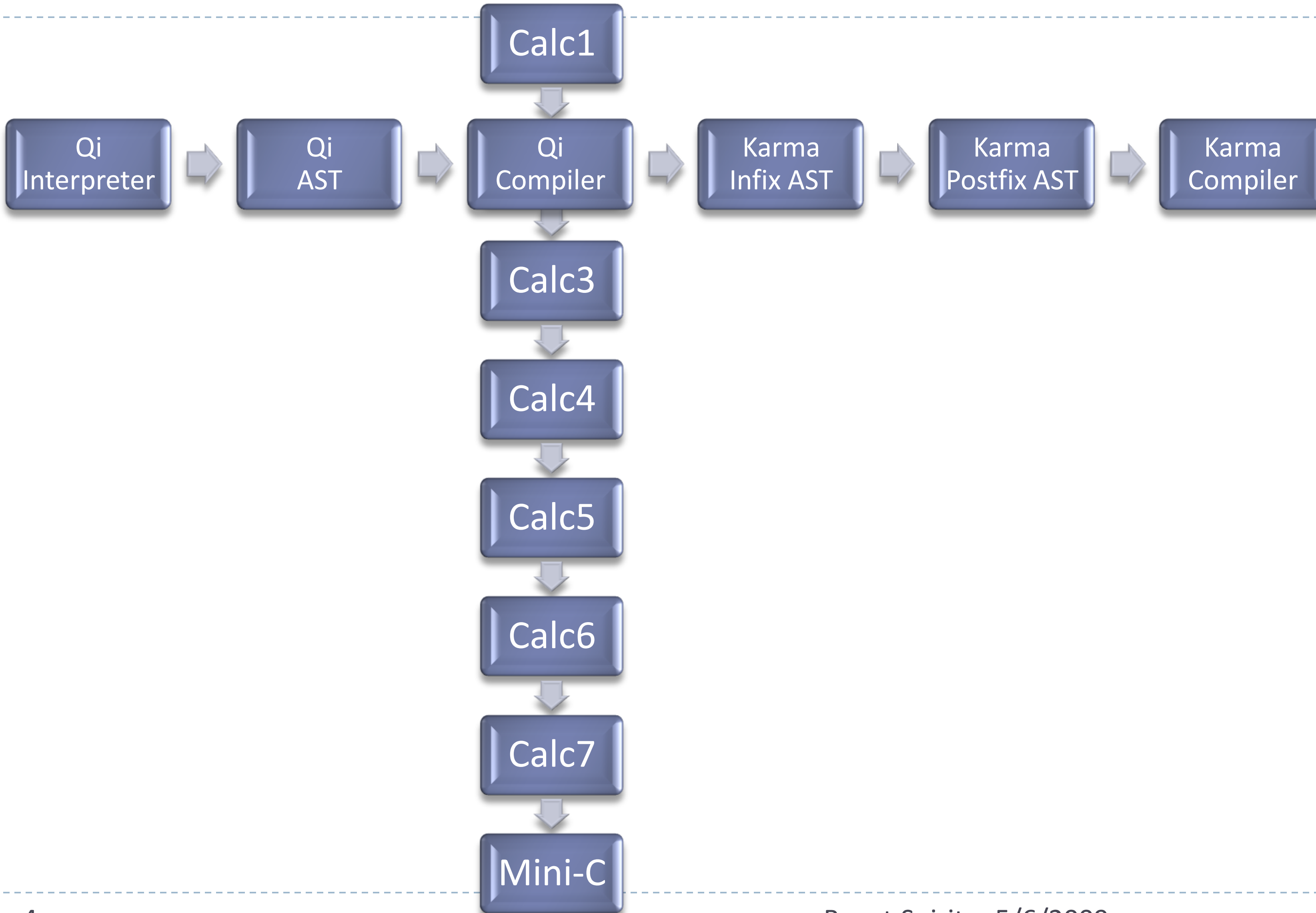
Agenda

- Overview
  - What's Spirit
  - Library Structure and Components
- Spirit.Classic
- Spirit.Qi and Spirit.Karma
  - Spirit.Qi
    - Building a simple VM compiler
  - Spirit.Karma
    - Data formatting and generation made easy

What's Boost.Spirit?

- A object oriented, recursive-descent parser and output generation library for C++
  - Implemented using template meta-programming techniques
  - Syntax of Parsing Expression Grammars (PEG's) directly in C++, used for input and output format specification
- Target grammars written entirely in C++
  - No separate tools to compile grammar
  - Seamless integration with other C++ code
  - Immediately executable
- Domain Specific Embedded Languages for
  - Token definition (spirit::`lex`)
  - Parsing (spirit::`qi`)
  - Output generation (spirit::`karma`)

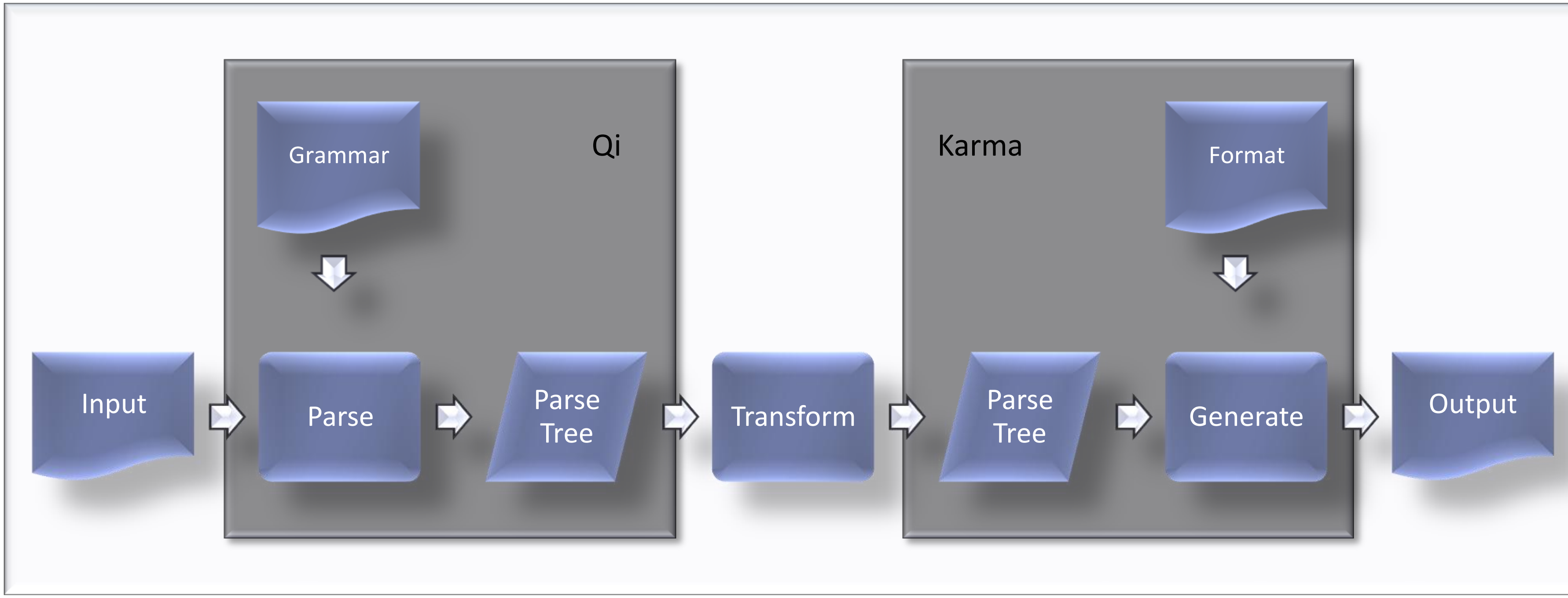
Overview


Calc1
Qi Interpreter
Qi AST
Qi Compiler
Karma Infix AST
Karma Postfix AST
Karma Compiler
Calc3
Calc4
Calc5
Calc6
Calc7
Mini-C

Where to get the stuff

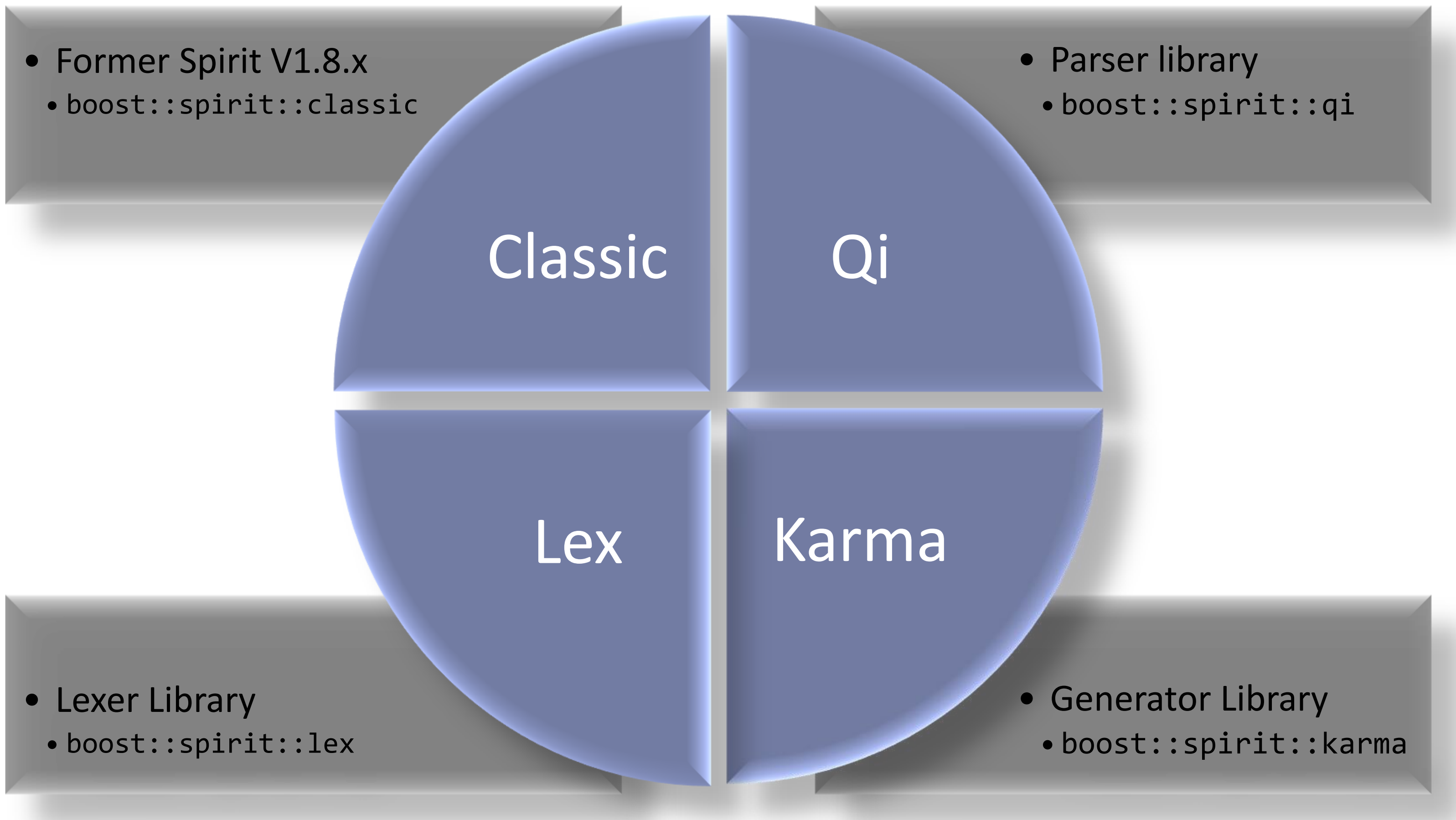
- Spirit V2.1:
  - Now fully integrated with Boost SVN::trunk
  - Separate download: will be made available
  - Will be released as part of Boost V1.40
- Mailing lists:
  - Spirit mailing list: http://sourceforge.net/mail/?group_id=28447

What's Boost.Spirit?



- Provides two independent but well integrated components of the text processing transformation chain: Parsing (Qi) and Output generation (Karma)

Library Structure



Spirit Components

- Spirit Classic (`spirit::classic`)
- Create lexical analyzers (`spirit::lex`)
  - Token definition (patterns, values, lexer states)
  - Semantic actions, i.e. attach code to matched tokens
- Parsing (`spirit::qi`)
  - Grammar specification
    - Token sequence definition
    - Semantic actions, i.e. attaching code to matched sequences
    - Parsing expression grammar (PEG)
    - Error handling
- Output generation (`spirit::karma`)
  - Grammar specification
    - Same as above
  - Formatting directives
    - Alignment, whitespace delimiting, line wrapping, indentation

Spirit.Classic

Former Spirit V1.8.x

Spirit.Classic

- Former Spirit V1.8.x
  - Existing applications compile unchanged
    - But lots of deprecated header warnings
  - To remove the warnings:
    - Included headers
      - Modify:

```
#include <boost/spirit/core.hpp>
```
to
```
#include <boost/spirit/include/classic_core.hpp>
```

    - Namespace references
      - Change:

```
namespace boost::spirit
```
to
```
namespace boost::spirit::classic
```

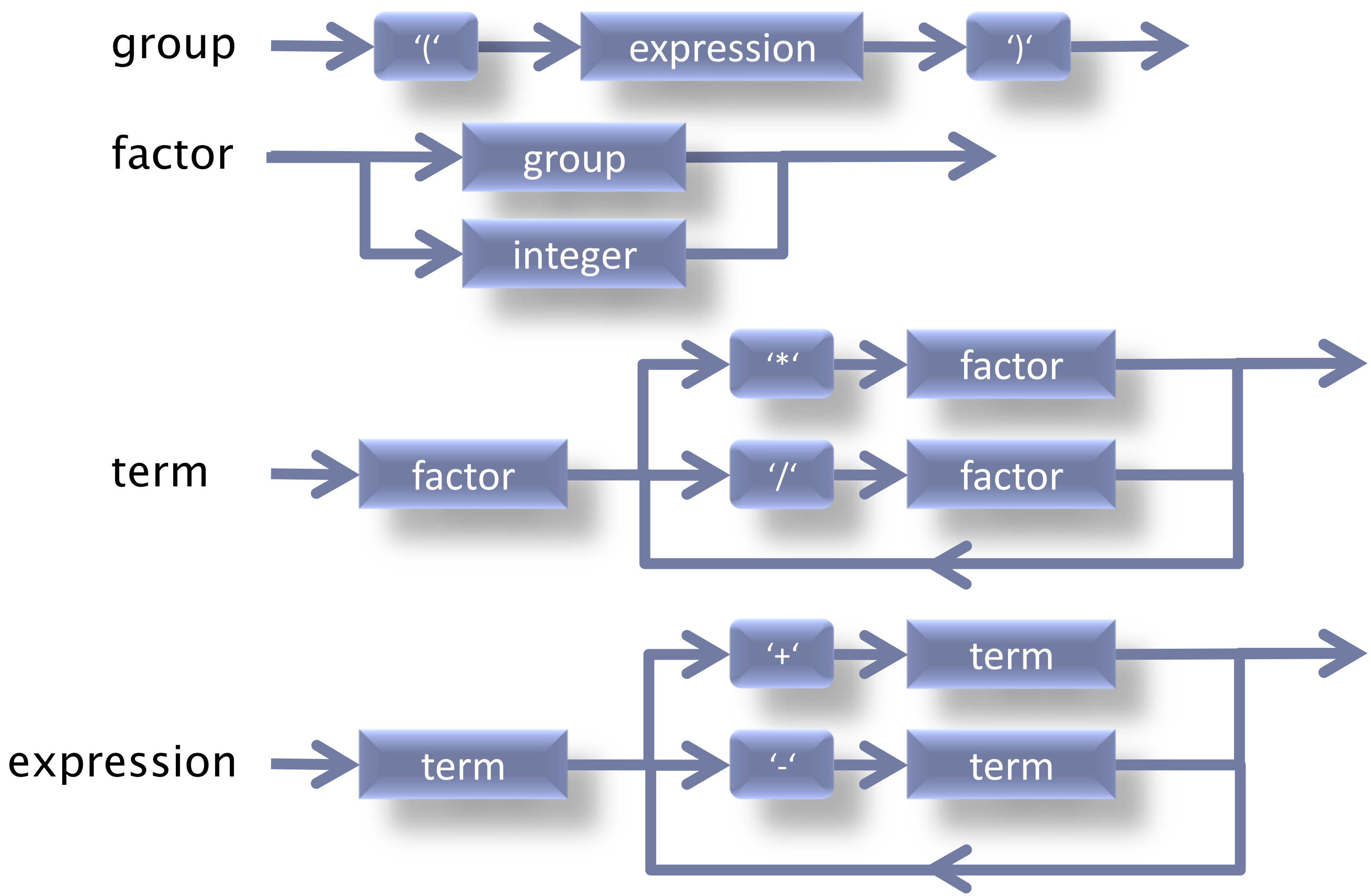
      - Or define:

```
#define BOOST_SPIRIT_USE_OLD_NAMESPACE 1
```

Spirit.Qi and Spirit.Karma

The Yin and Yang of Parsing and Output Generation

Syntax Diagram



Parsing Expression Grammar

- Formal grammar for describing a formal language in terms of a set of rules used to recognize strings of this language
- Does not require a tokenization stage
  - But it doesn't prevent it
- Similar to regular expressions being added to the Extended Backus-Naur Form (EBNF)
- Unlike (E)BNF, PEG's are not ambiguous
  - Exactly one valid parse tree for each PEG
- Any PEG can be directly represented as a recursive-descent parser
- Different Interpretation as EBNF
  - Greedy Loops
  - First come first serve alternates

Infix Calculator Grammar

Using Parsing Expression Grammars:

```
fact ← integer / '('    expr    ')'
term ← fact     (('*'    fact) / ('/'    fact))*
expr ← term     (('+'    term) / ('-'    term))*
```

Recap: Anatomy of a RD parser

```
fact  ← integer / '('   expr   ')'
term  ← fact      (('*'   fact) / ('/'   fact))*
expr  ← term      (('+'   term) / ('-'   term))*
```

- A **recursive descent parser** is a top-down parser built from a set of mutually-recursive procedures, each representing one of the grammar elements
- Thus the structure of the resulting program closely mirrors that of the grammar it recognizes
- Elements:
  - Terminals (primitives, i.e. plain characters, `integer`, etc.)
  - Nonterminals (`fact`, `term`, `expr`)
  - Sequences
  - Alternatives ('/')
  - Modifiers (kleene '*', plus '+', etc.)

Recap: Anatomy of a RD parser

- Elements:
  - Primitives (plain characters, `uint_`, etc.)
    ```
    bool match_char(char ch)
        { return ch == input(); }
    ```
  - Sequences
    ```
    bool match_sequence(F1 f1, F2 f2)
        { return f1() && f2(); }
    ```
  - Alternatives
    ```
    bool match_alternative(F1 f1, F2 f2)
        { return f1() || f2(); }
    ```
  - Modifiers (kleen, plus, etc.)
    ```
    bool match_kleene(F f)
        { while (f()); return true; }
    ```
  - Nonterminals (`fact`, `term`, `expr`)
    ```
    bool match_rule()
        { return match_embedded(); }
    ```

Recap: Anatomy of a RD parser

```
// fact  ← integer / '('   expr   ')'
bool match_fact()
{
    return match_integer() ||
         ( match_char('(') && match_expr() && match_char(')') );
}

// term  ← fact    (('*'   fact) / ('/'   fact))*
bool match_term() { /*...*/ }

// expr  ← term    (('+'   term) / ('-'   term))*
bool match_expr() { /*...*/ }
```

Infix Calculator Grammar

Using Parsing Expression Grammars:

```
fact  ←  integer / '('    expr    ')'
term  ←  fact     (('*'    fact) / ('/'    fact))*
expr  ←  term     (('+'    term) / ('-'    term))*
```

Infix Calculator Grammar

Using Boost.Spirit:

```
using namespace boost::spirit;
typedef qi::rule<std::string::iterator> rule;
rule fact, term, expr;

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

Spirit versus PEG Operators

Description	PEG	Spirit
Sequence	a b	Qi: a >> b Karma: a << b
Alternative	a / b	a | b
Zero or more (Kleene star)	a*	*a
One or more	a+	+a
And-predicate	&a	&a
Not-predicate	!a	!a
Optional	a?	-a

More Spirit Operators

Description	Syntax
Sequential-or (non-shortcutting)	a || b
List	a % b
Permutation	a ^ b
Expect (Qi only)	a > b
Anchor (Karma only)	a < b
Semantic Action	a[f]

The Direct Parser API

- Parsing without skipping

```
int i = 0; char c = '\0';
parse ("1", int_, i);                     // i == 1
parse ("1a", int_ >> char_, i, c);        // i == 1, c == 'a'
```

- Parsing with skipping (phrase parsing)

```
int i = 0; char c = '\0';
parse ("    1", int_, space, i);          // i == 1
parse (" 1  a", int_ >> char_, space, i, c);
                                          // i == 1, c == 'a'
```

The Stream based Parser API

- Parsing without skipping

```
int i = 0; char c = '\0';
std::stringstream is("1");
is >> match(int_, i);                  // i == 1

is.str("1a");
is >> match(int_, i, c);               // i == 1, c == 'a'
```

- Parsing with skipping

```
int i = 0; char c = '\0';
std::stringstream is("   1");
is >> match(int_, i);                  // i == 1

is.str("   1  a");
is >> phrase_match(int_, i, c);        // i == 1, c == 'a'
```

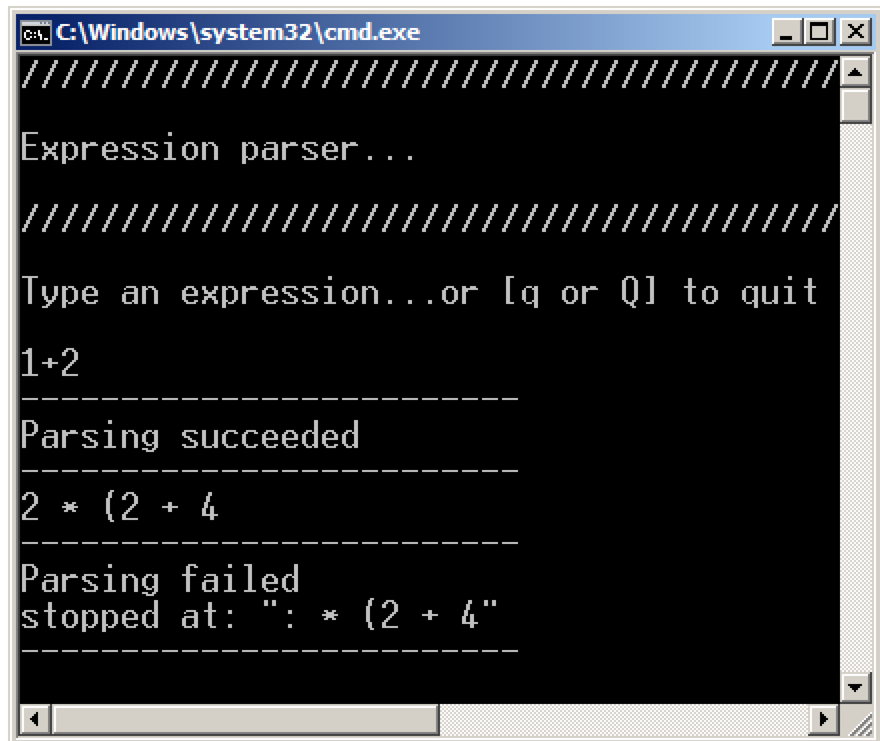
Spirit.Qi

Parser Library

In traditional Chinese culture, Qi (氣) is an active principle forming part of any living thing. It is frequently translated as "energy flow", or "vitalism".

A Calculator: The Parser

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

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

factor =
        uint_
    |   '(' >> expression >> ')'
    |   '-' >> factor
    |   '+' >> factor
    ;
```



More about Parsers and Generators

- Currently recursive-descent implementation
- Spirit makes the compiler generate format driven parser and generator routines
  - The (template) expression tree is directly converted into a corresponding parser/generator execution tree
- Parsers and generators are fully attributed
  - Each component either provides or expects a value of a specific type

A Calculator: The Interpreter

```
template <typename Iterator>
struct calculator
  : grammar_def<Iterator>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator>
        expression, term, factor;
};
```

A Calculator: The Interpreter

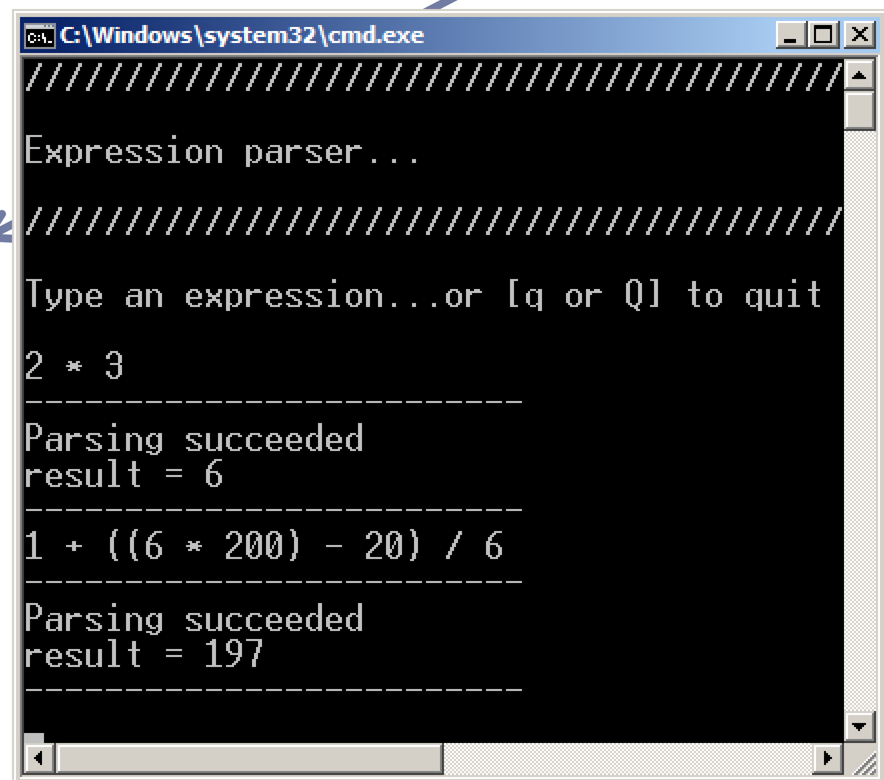
```
template <typename Iterator>
struct calculator
  : grammar_def<Iterator, int()>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, int()>
        expression, term, factor;
};
```

Grammar and Rule Signature

A Calculator: The Interpreter

```
expression =
    term                    [ _val = _1 ]
    >> *(   '+' >> term     [ _val += _1 ]
        |   '-' >> term     [ _val -= _1 ]
        )
    ;

term =
    factor                  [ _val = _1 ]
    >> *(   '*' >> factor   [ _val *= _1 ]
        |   '/' >> factor   [ _val /= _1 ]
        )
    ;

factor =
        uint_               [ _val = _1 ]
    |   '(' >> expression   [ _val = _1 ]     >>
    |   '-' >> factor       [ _val = -_1 ]
    |   '+' >> factor       [ _val = _1 ]
    ;
```

Semantic Actions



Semantic Actions

- Construct allowing to attach code to a parser component
  - Gets executed *after* successful invocation of the parser
  - May *receive* values from the parser to store or manipulate
  - May use local variables or rule arguments

- Syntax:

```
int i = 0;
int_[ref(i) = _1]
```

- Easiest way to write semantic actions is phoenix
  - `_1, _2, …` refer to elements of parser
  - `_a, _b, …` refer to locals (for `rule<>`'s)
  - `_r1, _r2, …` refer to arguments (for `rule<>`'s))
  - `pass` allows to make match fail (by assigning false)

Semantic Actions

- Any function or function object can be called

```
void f(Attribute const&, Context&, bool&);
void f(Attribute const&, Context&);
void f(Attribute const&);
void f();
```

- Attribute
  - Simple parser: just the attribute value
  - Compound generator: `fusion::vector<A1, A2, …>` (AN: attributes of single parsers)
- Context
  - Normally `unused_type` (except for `rule<>`'s and `grammar<>`'s, where this is a complex data structure)
  - Can be used to access rule's locals and attributes
- bool
  - Allows to make the parser fail (by assigning `false`)

Semantic Actions

- Plain function:

```
void write(int const& i) { std::cout << i; }
int_[write]
```

- But it's possible to use `boost::lambda`...

```
using boost::lambda::_1;
int_[std::cout << _1]
```

- ... and `boost::bind` as well

```
void write(int const& i) { std::cout << i; }
int_[boost::bind(&write, _1)]
```

A Calculator: The Compiler

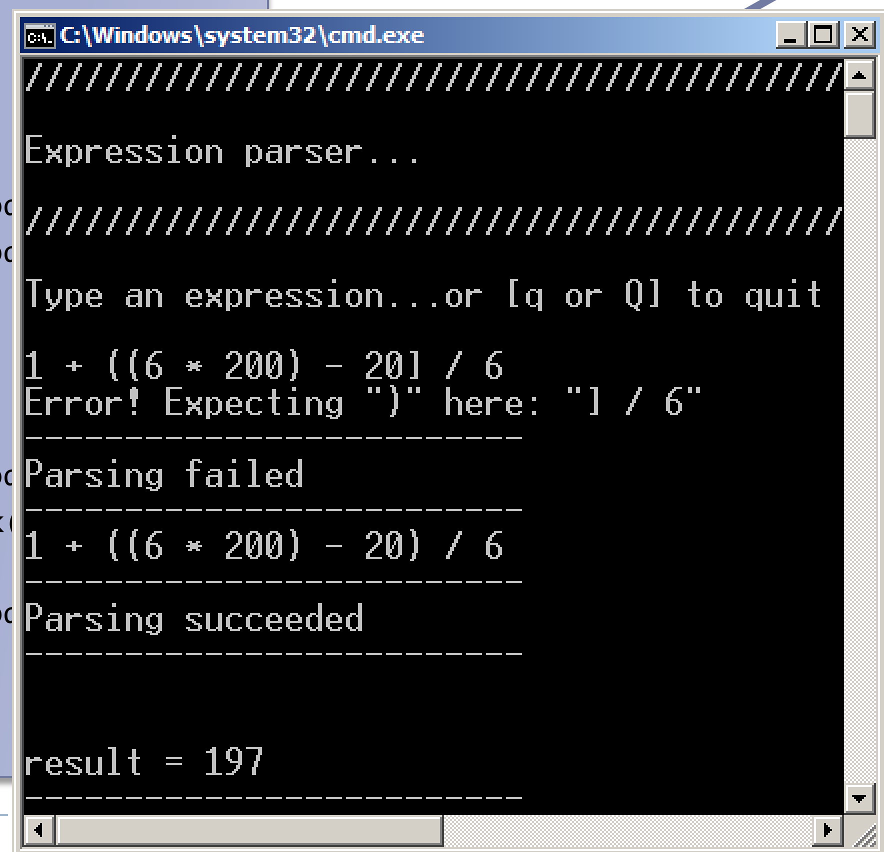
```
expression =
    term
    >> *(   '+'   > term        [ push_back(code, op_add) ]
        |   '-'   > term        [ push_back(code, op_sub) ]
        )
    ;

term =
    factor
    >> *(   '*'   > factor      [ push_back(code, op_mul) ]
        |   '/'   > factor      [ push_back(code, op_div) ]
        )
    ;

factor =
        uint_                   [ push_back(code, op_int),
                                      push_back(code, _1) ]
    |   '('       > expression > ')'
    |   '-'       > factor      [ push_back(code, op_neg) ]
    |   '+'       > factor
    ;
```

Expectation Points

A Calculator: The Compiler

```
expression =
    term
    >> *(   '+'  > term          [ push_back(code, op_add) ]
        |   '-'  > term          [ push_back(code, op_sub) ]
        )
    ;

term =
    factor
    >> *(   '*'  > factor        [ push_back(coc
        |   '/'  > factor        [ push_back(coc
        )
    ;

factor =
        uint_                    [ push_back(coc
                                      push_back(
    |   '('      > expression > ')'
    |   '-'      > factor        [ push_back(coc
    |   '+'      > factor
    ;
```

The Compiler



A Calculator: Creating an AST

- Here is the AST (simplified):

```
// A node of the AST holds either an integer, a binary
// operation description, or a unary operation description
struct ast_node
{
    boost::variant<int, binary_op, unary_op> expr;
};

// For instance, a unary_op holds the description of the
// operation and a node of the AST
struct unary_op
{
    char op;             // '+' or '-'
    ast_node subject;
};
```

A Calculator: Creating an AST

```
template <typename Iterator>
struct calculator
  : grammar_def<Iterator>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator>
        expression, term, factor;
};
```

A Calculator: Creating an AST

```
template <typename Iterator>
struct calculator
  : grammar_def<Iterator, ast_node()>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, ast_node()>
        expression, term, factor;
};
```

Grammar and Rule Signature

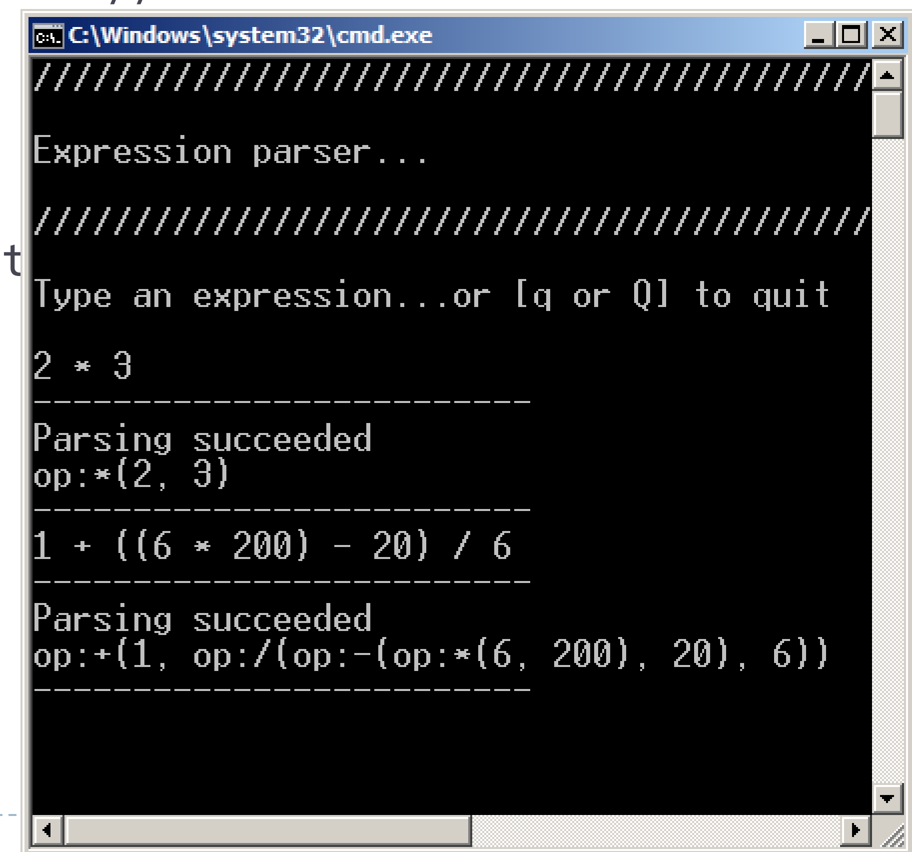
A Calculator: Creating an AST

```
expression =
    term                    [_val = _1]
    >> *(   '+'   > term    [_val += _1]
        |   '-'   > term    [_val -= _1]
        )
    ;

term =
    factor                  [_val = _1]
    >> *(   '*'   > factor  [_val *= _1]
        |   '/'   > factor  [_val /= _1]
        )
    ;

factor =
        uint_               [_val = _1]
    |   '('   > expression  [_val = _1]         > ')'
    |   '-'   > factor      [_val = neg(_1)]
    |   '+'   > factor      [_val = pos(_1)]
    ;
```

Semantic Actions

A Calculator: Creating an AST

```
calculator calc;            // our calculator grammar
ast_node ast;               // our instance of the AST
std::string str("2*3");

// do it!
if (parse (str.begin(), st
    print_ast(ast);
```



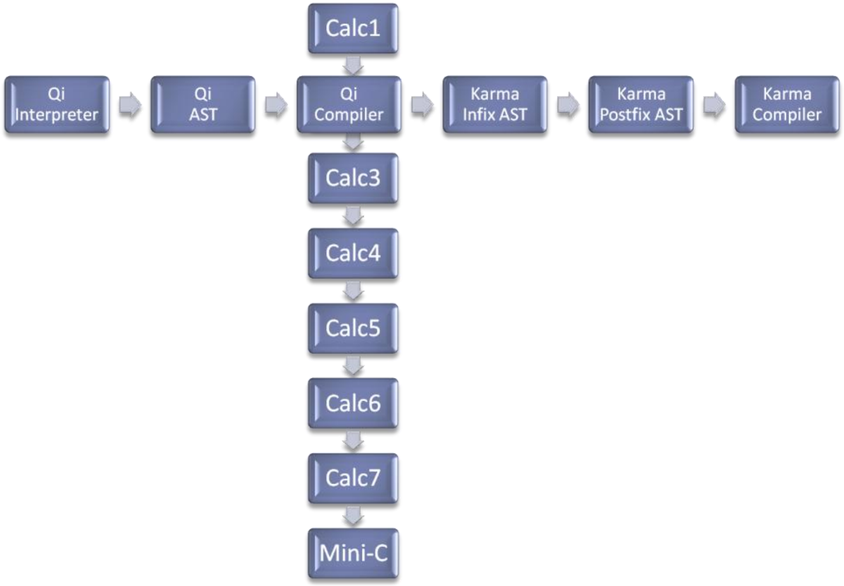
Parser Types and their Attributes

	Qi Parser Types	Attribute Type
Literals	• 'a', "abc", double_(1.0)	• No attribute
Primitive components	• int_, char_, double_, … • bin, oct, hex • byte, word, dword, qword, … • stream • symbol<A>	• int, char, double, … • int • uint8_t, uint16_t, uint32_t, int64_t, … • boost::any • Explicitely specified (A)
Non-terminals	• rule<A()>, grammar<A()>	• Explicitely specified (A)
Operators	• *a (kleene) • +a (one or more) • -a (optional) • a % b (list) • a >> b (sequence) • a | b (alternative) • &a, !a (predicates/eps) • a ^ b (permutation)	• std::vector<A> • std::vector<A> • boost::optional<A> • std::vector<A> • fusion::vector<A, B> • boost::variant<A, B> • No attribute • fusion::vector<optional<A>, optional<B> >
Directives	• lexeme[a], omit[a], nocase[a] • raw[]	• A • boost::iterator_range<Iterator>
Semantic action	• a[f]	• A

Spirit.Qi

Building a simple language compiler

Overview



- **Calc1** Expression parser
- **Calc2**
  - Semantic Actions
  - AST
- **Calc3** Interpreter
- **Calc4** Error handling and reporting
- **Calc5** Byte-Code Compiler
- **Calc6** Statements
- **Calc7** Boolean expressions and control structures
- **mini_c** Full fledged minimal C-like programming language

PEG

```
group        ← '(' expression ')'
factor       ← integer / group
term         ← factor (('*' factor) / ('/' factor))*
expression   ← term (('+' term) / ('-' term))*
```

EBNF (ISO/IEC 14977)

```
group       = "(" , expression , ")";
factor      = integer | group;
term        = factor , (("*" , factor) | ("/" , factor))*;
expression  = term , (("+" , term) | ("-" , term))*;
```

Spirit DSEL hosted by C++

```
group       = '(' >> expression >> ')';
factor      = uint_ | group;
term        = factor >> *(('*' >> factor) | ('/' >> factor));
expression  = term >> *(('+' >> term) | ('-' >> term));
```

Spirit DSEL hosted by C++

```
group       = '(' >> expression >> ')';
factor      = uint_ | group;
term        = factor >> *(('*' >> factor) | ('/' >> factor));
expression  = term >> *(('+' >> term) | ('-' >> term));
```

calc1.cpp

- Simple expression parser
- Syntax checker
- No semantic evaluation (no semantic actions)

```
template <typename Iterator>
struct calculator : grammar_def<Iterator, space_type>
{
    calculator()
    {
        expression =
            term
            >> *(   ('+' >> term)
                |   ('-' >> term)
                )
            ;

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

        factor =
            uint_
            |   '(' >> expression >> ')'
            |   ('-' >> factor)
            |   ('+' >> factor)
            ;
    }

    rule<Iterator, space_type> expression, term, factor;
};
```

```
template <typename Iterator>
struct calculator
  : grammar_def<Iterator, space_type>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, space_type>
        expression, term, factor;
};
```

```cpp
typedef std::string::const_iterator iterator_type;
typedef calculator<iterator_type> calculator;

//  Our grammar definition
calculator def;

// Our grammar
grammar<calculator> calc(def, def.expression);

// Parse!
std::string::const_iterator iter = str.begin();
std::string::const_iterator end = str.end();
bool r = phrase_parse(iter, end, calc, space);
```

calc2.cpp

- Semantic actions using plain functions
- No evaluation
- Prints code suitable for a stack based virtual machine

```
expression =
    term
    >> *(   ('+' >> term                [&do_add])
        |   ('-' >> term                [&do_subt])
        )
    ;

term =
    factor
    >> *(   ('*' >> factor              [&do_mult])
        |   ('/' >> factor              [&do_div])
        )
    ;

factor =
    uint_                               [&do_int]
    |   '(' >> expression >> ')'
    |   ('-' >> factor                  [&do_neg])
    |   ('+' >> factor)
    ;
```

Semantic Actions

```
void do_int(int n)
{ std::cout << "push " << n << std::endl; }

void do_add()
{ std::cout << "add\n"; }

void do_subt()
{ std::cout << "subtract\n"; }

void do_mult()
{ std::cout << "mult\n"; }

void do_div()
{ std::cout << "divide\n"; }

void do_neg()
{ std::cout << "negate\n"; }
```

```
1 * 2
```

```
push 1
push 2
mult
```

```
1 + ((6 * 200) - 20) / 6
```

```
push 1
push 6
push 200
mult
push 20
subtract
push 6
divide
add
```

calc3.cpp

- Expression evaluation
- Using phoenix semantic actions
- The parser is an "interpreter" that evaluates expressions on the fly

calc2.cpp

```
template <typename Iterator>
struct calculator
  : grammar<Iterator, space_type>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, space_type>
        expression, term, factor;
};
```

calc3.cpp

```
template <typename Iterator>
struct calculator
  : grammar<Iterator, int(), space_type>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, int(), space_type>
        expression, term, factor;
};
```

calc3.cpp

```
template <typename Iterator>
struct calculator
  : grammar<Iterator, int(), space_type>
{
    calculator()
    { /*…definition here*/ }

    rule<Iterator, int(), space_type>
        expression, term, factor;
};
```

Grammar and Rule Signature

Attributes

- **Synthesized Attribute** == Function result
  - Used to pass semantic information up the parse tree
- **Inherited Attribute** == Function parameters
  - Used to pass semantic information down from parent nodes

`int(int, char)`

Synthesized
Attribute

```
int(int, char)
```

Inherited
Attributes

```
expression =
    term                            [_val = _1]
    >> *(   ('+' >> term            [_val += _1])
        |   ('-' >> term            [_val -= _1])
        )
    ;

term =
    factor                          [_val = _1]
    >> *(   ('*' >> factor          [_val *= _1])
        |   ('/' >> factor          [_val /= _1])
        )
    ;

factor =
    uint_                           [_val = _1]
    |   '(' >> expression           [_val = _1] >> ')'
    |   ('-' >> factor              [_val = -_1])
    |   ('+' >> factor              [_val = _1])
    ;
```

Semantic Actions

```
expression =
    term                            [_val = _1]
    >> *(   ('+' >> term            [_val += _1])
        |   ('-' >> term            [_val -= _1])
        )
    ;

term =
    factor                          [_val = _1]
    >> *(   ('*' >> factor          [_val *= _1])
        |   ('/' >> factor          [_val /= _1])
        )
    ;

factor =
    uint_                           [_val = _1]
    |   '(' >> expression           [_val = _1] >> ')'
    |   ('-' >> factor              [_val = -_1])
    |   ('+' >> factor              [_val = _1])
    ;
```

Synthesized Attribute Placeholder

```
1 + 2
```

```
result = 3
```

```
1 + ((6 * 200) - 20) / 6
```

```
result = 197
```

Calc2 with AST

```
expression =
          term                                [_val = _1]
          >> *(   ('+' >> term                [_val += _1])
              |   ('-' >> term                [_val -= _1])
              )
          ;

      term =
          factor                              [_val = _1]
          >> *(   ('*' >> factor              [_val *= _1])
              |   ('/' >> factor              [_val /= _1])
              )
          ;

      factor =
          uint_                               [_val = _1]
          |   '(' >> expression               [_val = _1] >> ')'
          |   ('-' >> factor                  [_val = neg(_1)])
          |   ('+' >> factor                  [_val = pos(_1)])
          ;
```

The AST

Here is the AST:

```
struct expression_ast
{
    typedef
        boost::variant<
            int,
            boost::recursive_wrapper<binary_op>,
            boost::recursive_wrapper<unary_op>
        >
    type;

    type expr;
};
```

calc4.cpp

- Similar to calc3
- This time, we'll incorporate error handling and reporting

```
expression =
    term                                [_val = _1]
    >> *(   ('+' > term                 [_val += _1])
        |   ('-' > term                 [_val -= _1])
        )
    ;

term =
    factor                              [_val = _1]
    >> *(   ('*' > factor               [_val *= _1])
        |   ('/' > factor               [_val /= _1])
        )
    ;

factor =
    uint_                               [_val = _1]
    |   '(' > expression                [_val = _1] > ')'
    |   ('-' > factor                   [_val = -_1])
    |   ('+' > factor                   [_val = _1])
    ;
```

```
expression =
    term                            [_val = _1]
    >> *(   ('+' > term             [_val += _1])
        |   ('-' > term             [_val -= _1])
        )
    ;

term =
    factor                          [_val = _1]
    >> *(   ('*' > factor           [_val *= _1])
        |   ('/' > factor           [_val /= _1])
        )
    ;

factor =
    uint_                           [_val = _1]
    |   '(' > expression            [_val = _1] > ')'
    |   ('-' > factor               [_val = -_1])
    |   ('+' > factor               [_val = _1])
    ;
```

Expectations!!!

```
expression.name("expression");
term.name("term");
factor.name("factor");

on_error<fail>
(
    expression
  , std::cout
        << val("Error! Expecting ")
        << _4
        << val(" here: \"")
        << construct<std::string>(_3, _2)
        << val("\"")
        << std::endl
);
```

```
expression.name("expression");
term.name("term");
factor.name("factor");
```

Naming the Rules

```
on_error<fail>
(
    expression
  , std::cout
        << val("Error! Expecting ")
        << _4
        << val(" here: \"")
        << construct<std::string>(_3, _2)
        << val("\"")
        << std::endl
);
```

```
expression.name("expression");
term.name("term");
factor.name("factor");

on_error<fail>
(
    expression
  , std::cout
        << val("Error! Expecting ")
        << _4
        << val(" here: \"")
        << construct<std::string>(_3, _2)
        << val("\"")
        << std::endl
);
```

What failed?

```
expression.name("expression");
term.name("term");
factor.name("factor");

on_error<fail>
(
    expression
  , std::cout
        << val("Error! Expecting ")
        << _4
        << val(" here: \"")
        << construct<std::string>(_3, _2)
        << val("\"")
        << std::endl
);
```

Iterators to error-position and end of input

```
expression.name("expression");
term.name("term");
factor.name("factor");

on_error<fail>
(
    expression
  , std::cout
        << val("Error! Expecting ")
        << _4
        << val(" here: \"")
        << construct<std::string>(_3, _2)
        << val("\"")
        << std::endl
);
```

On Error, Fail Parsing

```
1 + ((6 * 200) - 20] / 6
```

```
Error! Expecting ')' here: "] / 6"
```

```
'(' > expression > ')'
```

$#@!

- `1 + banana`

```
Error! Expecting term here: " banana"
```

```
'+' > term
```

$#@!

calc5.cpp

- Compiler to a simple VM
- Same-o-same-o calculator grammar
- Uses Phoenix to compile the byte codes

```
enum byte_code
{
    op_neg,     //  negate the top stack entry
    op_add,     //  add top two stack entries
    op_sub,     //  subtract top two stack entries
    op_mul,     //  multiply top two stack entries
    op_div,     //  divide top two stack entries
    op_int,     //  push constant integer into the
                //  stack
};
```

```
class vmachine
{
public:

    vmachine(unsigned stackSize = 4096)
      : stack(stackSize)
      , stack_ptr(stack.begin())
    {
    }

    int top() const { return stack_ptr[-1]; };
    void execute(std::vector<int> const& code);

private:

    std::vector<int> stack;
    std::vector<int>::iterator stack_ptr;
};
```

```
void vmachine::execute(
    std::vector<int> const& code)
{
    std::vector<int>::const_iterator pc = code.begin();
    stack_ptr = stack.begin();

    while (pc != code.end())
    {
        switch (*pc++)
        {
            /*...*/
        }
    }
}
```

```
case op_neg:
    stack_ptr[-1] = -stack_ptr[-1];
    break;

case op_add:
    --stack_ptr;
    stack_ptr[-1] += stack_ptr[0];
    break;

case op_sub:
    --stack_ptr;
    stack_ptr[-1] -= stack_ptr[0];
    break;
```

```
case op_mul:
    --stack_ptr;
    stack_ptr[-1] *= stack_ptr[0];
    break;

case op_div:
    --stack_ptr;
    stack_ptr[-1] /= stack_ptr[0];
    break;

case op_int:
    *stack_ptr++ = *pc++;
    break;
```

```
expression =
    term
    >> *(   ('+' > term         [push_back(ref(code), op_add)])
        |   ('-' > term         [push_back(ref(code), op_sub)])
        )
    ;

term =
    factor
    >> *(   ('*' > factor       [push_back(ref(code), op_mul)])
        |   ('/' > factor       [push_back(ref(code), op_div)])
        )
    ;

factor =
    uint_                       [
                                    push_back(ref(code), op_int),
                                    push_back(ref(code), _1)
                                ]
    |   '(' > expression > ')'
    |   ('-' > factor           [push_back(ref(code), op_neg)])
    |   ('+' > factor)
    ;
```

Our Compiler

calc6.cpp

- Variables and assignment
- Symbol table
- Grammar modularization. Grammars for:
  - expression
  - Statement
- Local variables
- Synthesized and Inherited Attributes
- The auto rule!
- “raw” (transduction parsing)

The VM updated

```
enum byte_code
{
    op_neg,     //  negate the top stack entry
    op_add,     //  add top two stack entries
    op_sub,     //  subtract top two stack entries
    op_mul,     //  multiply top two stack entries
    op_div,     //  divide top two stack entries

    op_load,    //  load a variable
    op_store,   //  store a variable
    op_int,     //  push constant integer
                //  into the stack
};
```

```
void vmachine::execute(
    std::vector<int> const& code, int nvars)
{
    std::vector<int>::const_iterator
        pc = code.begin();
    std::vector<int>::iterator
        locals = stack.begin();
    stack_ptr = stack.begin() + nvars;

    while (pc != code.end())
    {
        /*...*/
    }
}
```

```
case op_load:
    *stack_ptr++ = locals[*pc++];
    break;

case op_store:
    --stack_ptr;
    locals[*pc++] = stack_ptr[0];
    break;
```

Our expression grammar and compiler

```
template <typename Iterator>
struct expression : grammar<Iterator, space_type>
{
    expression(
        std::vector<int>& code
      , symbols<char, int>& vars);

    rule<Iterator, space_type>
        expr, additive_expr, multiplicative_expr
      , unary_expr, primary_expr, variable;

    std::vector<int>& code;
    symbols<char, int>& vars;
    function<compile_op> op;
};
```

Our expression grammar and compiler

```
template <typename Iterator>
struct expression : grammar<Iterator, space_type>
{
    expression(
        std::vector<int>& code
      , symbols<char, int>& vars);

    rule<Iterator, space_type>
        expr, additive_expr, multiplicative_expr
      , unary_expr, primary_expr, variable;

    std::vector<int>& code;
    symbols<char, int>& vars;
    function<compile_op> op;
};
```

The byte codes

Our expression grammar and compiler

```
template <typename Iterator>
struct expression : grammar<Iterator, space_type>
{
    expression(
        std::vector<int>& code
      , symbols<char, int>& vars);

    rule<Iterator, space_type>
        expr, additive_expr, multiplicative_expr
      , unary_expr, primary_expr, variable;

    std::vector<int>& code;
    symbols<char, int>& vars;
    function<compile_op> op;
};
```

The Symbol Table

Our expression grammar and compiler

```
template <typename Iterator>
struct expression : grammar<Iterator, space_type>
{
    expression(
        std::vector<int>& code
      , symbols<char, int>& vars);

    rule<Iterator, space_type>
        expr, additive_expr, multiplicative_expr
      , unary_expr, primary_expr, variable;

    std::vector<int>& code;
    symbols<char, int>& vars;
    function<compile_op> op;
};
```

A Phoenix function that compiles byte codes

Our expression grammar and compiler

```
template <typename Iterator>
struct expression : grammar<Iterator, space_type>
{
    expression(
        std::vector<int>& code
      , symbols<char, int>& vars);

    rule<Iterator, space_type>
        expr, additive_expr, multiplicative_expr
      , unary_expr, primary_expr, variable;

    std::vector<int>& code;
    symbols<char, int>& vars;
    function<compile_op> op;
};
```

Renaming the rules and adding some more

Our expression grammar and compiler (Part 1)

```
expr =
    additive_expr.alias()
    ;

additive_expr =
    multiplicative_expr
    >> *(   ('+' > multiplicative_expr  [op(op_add)])
        |   ('-' > multiplicative_expr  [op(op_sub)])
        )
    ;

multiplicative_expr =
    unary_expr
    >> *(   ('*' > unary_expr           [op(op_mul)])
        |   ('/' > unary_expr           [op(op_div)])
        )
    ;
```

Our expression grammar and compiler (Part 2)

```
unary_expr =
        primary_expr
    |   ('-' > primary_expr                     [op(op_neg)])
    |   ('+' > primary_expr)
    ;

primary_expr =
    uint_                                       [op(op_int, _1)]
    |   variable
    |   '(' > expr > ')'
    ;

variable =
    (
        lexeme[
            vars
            >> !(alnum | '_')                   // make sure we have whole words
        ]
    )                                           [op(op_load, _1)]
    ;
```

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;


    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;


    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Some Phoenix functions

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;


    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Rule with int synthesized attribute

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;


    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Rule with void synthesized attribute And int inherited attribute

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;


    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Rule with int local variable

Our statement grammar and compiler

```
template <typename Iterator>
struct statement : grammar<Iterator, space_type>
{
    statement(std::vector<int>& code);

    std::vector<int>& code;
    symbols<char, int> vars;
    int nvars;

    expression<Iterator> expr;
    rule<Iterator, space_type> start, var_decl;
    rule<Iterator, std::string(), space_type> identifier;
    rule<Iterator, int(), space_type> var_ref;
    rule<Iterator, locals<int>, space_type> assignment;
    rule<Iterator, void(int), space_type> assignment_rhs;

    function<var_adder> add_var;
    function<compile_op> op;
};
```

Embedding the expression grammar

Our statement grammar and compiler (Part1)

```
identifier %=
    raw[lexeme[alpha >> *(alnum | '_')]]
    ;

var_ref =
    lexeme
    [
            vars        [_val = _1]
        >>  !(alnum | '_') // make sure we have whole words
    ]
    ;

var_decl =
        "var"
    >   !var_ref        // make sure the variable isn't redeclared
    >   identifier      [add_var(_1, ref(nvars))]
    >   (';' | '=' > assignment_rhs(ref(nvars)-1))
    ;
```

Our statement grammar and compiler (Part1)

```
identifier %=
    raw[lexeme[alpha >> *(alnum | '_')]]
    ;

var_ref =
    lexeme
    [
            vars        [_val = _1]
        >>  !(alnum | '_') // make sure we have whole words
    ]
    ;

var_decl =
        "var"
    >   !var_ref        // make sure the variable isn't redeclared
    >   identifier      [add_var(_1, ref(nvars))]
    >   (';' | '=' > assignment_rhs(ref(nvars)-1))
    ;
```

Transduction

Our statement grammar and compiler (Part1)

```
identifier %=
    raw[lexeme[alpha >> *(alnum | '_')]]
    ;

var_ref =
    lexeme
    [
            vars        [_val = _1]
        >>  !(alnum | '_') // make sure we have whole words
    ]
    ;

var_decl =
        "var"
    >   !var_ref        // make sure the variable isn't redeclared
    >   identifier      [add_var(_1, ref(nvars))]
    >   (';' | '=' > assignment_rhs(ref(nvars)-1))
    ;
```

What is that?

Our statement grammar and compiler (Part1)

Auto rule operator!

```
identifier %=
    raw[lexeme[alpha >> *(alnum | '_')]]
    ;

var_ref =
    lexeme
    [
            vars        [_val = _1]
        >>  !(alnum | '_') // make sure we have whole words
    ]
    ;

var_decl =
        "var"
    >   !var_ref        // make sure the variable isn't redeclared
    >   identifier      [add_var(_1, ref(nvars))]
    >   (';' | '=' > assignment_rhs(ref(nvars)-1))
    ;
```

```
a_rule %= some-expression;
```

Is equivalent to:

```
a_rule = some-expression
         [
             val_ = _1
         ];
```

Recall:

- Parsers have a corresponding (synthesized) attribute.
- The Rule has an explicitly specified (synthesized) attribute.

Parser Types and their Attributes

	Qi parser types	Attribute Type
Primitive components	• int_, char_, double_, … • bin, oct, hex • byte, word, dword, qword, … • stream • typed_stream<A> • symbol<A>	• int, char, double, … • int • uint8_t, uint16_t, uint32_t, int64_t, … • spirit::hold_any (~ boost::any) • Explicitely specified (A) • Explicitely specified (A)
Non-terminals	• rule<A()>, grammar<A()>	• Explicitely specified (A)
Operators	• *a (kleene) • +a (one or more) • -a (optional) • a % b (list) • a >> b (sequence) • a | b (alternative) • &a (predicate/eps) • !a (not predicate) • a ^ b (permutation)	• std::vector<A> • std::vector<A> • boost::optional<A> • std::vector<A> • fusion::vector<A, B> • boost::variant<A, B> • No attribute • No attribute • fusion::vector<boost::optional<A>, boost::optional<B> >
Directives	• lexeme[a], omit[a], nocase[a] … • raw[]	• A • boost::iterator_range<Iterator>
Semantic action	• a[f]	• A

When you have:

```
a_rule = some-expression;
```

Where the attribute of *a_rule* "is compatible with" the attribute of *some-expression*…

You can write it as:

a_rule %= some-expression;

Whereby the attribute of *some-expression* is automatically assigned to *a_rule*.

No need for semantic actions!

Our statement grammar and compiler (Part1)

```
identifier %= raw[lexeme[alpha >> *(alnum | '_')]];
```

std::string ← boost::iterator_range<Iterator>

boost::iterator_range<Iterator> is compatible with std::string if Iterator points to a char.
Both are STL sequences with begin/end.

Back to our statement grammar and compiler (Part1)

```
identifier %=
    raw[lexeme[alpha >> *(alnum | '_')]]
    ;

var_ref =
    lexeme
    [
            vars        [_val = _1]
        >>  !(alnum | '_') // make sure we have whole words
    ]
    ;

var_decl =
        "var"
    >   !var_ref        // make sure the variable isn't redeclared
    >   identifier      [add_var(_1, ref(nvars))]
    >   (';' | '=' > assignment_rhs(ref(nvars)-1))
    ;
```

Statement grammar and compiler (Part2)

```
assignment =
        var_ref             [_a = _1]
    >>  '='
    >   assignment_rhs(_a)
    ;

assignment_rhs =
        expr
    >   char_(';')          [op(op_store, _r1)]
    ;

start = +(var_decl | assignment);
```

Local Variable Placeholder

Statement grammar and compiler (Part2)

```
assignment =
        var_ref             [_a = _1]
    >>  '='
    >   assignment_rhs(_a)
    ;

assignment_rhs =
        expr
    >   char_(';')          [op(op_store, _r1)]
    ;

start = +(var_decl | assignment);
```

Inherited Attribute Placeholder

calc7.cpp

- Builds on calc6
- Boolean expressions
- Control structures

The VM updated again

```
op_not,        //  boolean negate the top stack entry
op_eq,         //  compare the top two stack entries for ==
op_neq,        //  compare the top two stack entries for !=
op_lt,         //  compare the top two stack entries for <
op_lte,        //  compare the top two stack entries for <=
op_gt,         //  compare the top two stack entries for >
op_gte,        //  compare the top two stack entries for >=

op_and,        //  logical and top two stack entries
op_or,         //  logical or top two stack entries

op_true,       //  push constant 0 into the stack
op_false,      //  push constant 1 into the stack

op_jump_if,    //  jump to an absolute position in the code if top stack
               //  evaluates to false
op_jump        //  jump to an absolute position in the code
```

```
case op_jump:
    pc = code.begin() + *pc;
    break;

case op_jump_if:
    if (!bool(stack_ptr[-1]))
        pc = code.begin() + *pc;
    else
        ++pc;
    --stack_ptr;
    break;
```

expression grammar updated

```
equality_expr =
    relational_expr
    >> *(   ("==" > relational_expr     [op(op_eq)])
        |   ("!=" > relational_expr     [op(op_neq)])
        )
    ;

relational_expr =
    logical_expr
    >> *(   ("<=" > logical_expr        [op(op_lte)])
        |   ('<' > logical_expr         [op(op_lt)])
        |   (">=" > logical_expr        [op(op_gte)])
        |   ('>' > logical_expr         [op(op_gt)])
        )
    ;

logical_expr =
    additive_expr
    >> *(   ("&&" > additive_expr       [op(op_and)])
        |   ("||" > additive_expr       [op(op_or)])
        )
    ;
```

statement grammar upgrade

```
rule<Iterator, space_type>
    statement_, statement_list, compound_statement
;

rule<Iterator, locals<int>, space_type> if_statement;
rule<Iterator, locals<int, int>, space_type> while_statement;
```

statement grammar upgrade (if statement part 1)

```
if_statement =
        lit("if")
    >>  '('
    >   expr            [
                            op(op_jump_if, 0), // we shall fill
                                               // this (0) in later
                            _a = size(ref(code))-1 // mark its position
                        ]
    >   ')'
    >   statement_      [
                            // now we know where to jump to
                            // (after the if branch)
                            ref(code)[_a] = size(ref(code))
                        ]
    >>
```

More… (else branch)

statement grammar upgrade (if statement part 2: else branch)

```
>>
   -(
        lexeme[
            "else"
            >> !(alnum | '_') // make sure we have whole words
        ]
                    [
                        ref(code)[_a] += 2, // adjust for the "else" jump
                        op(op_jump, 0), // we shall fill this (0) in later
                        _a = size(ref(code))-1 // mark its position
                    ]
    >   statement_  [
                        // now we know where to jump to
                        // (after the else branch)
                        ref(code)[_a] = size(ref(code))
                    ]
    )
;
```

statement grammar upgrade (2)

```
while_statement =
        lit("while")    [
                            _a = size(ref(code)) // mark our position
                        ]
    >>  '('
    >   expr            [
                            op(op_jump_if, 0), // we shall fill this
                                               // (0) in later
                            _b = size(ref(code))-1 // mark its position
                        ]
    >   ')'
    >   statement_      [
                            op(op_jump, _a), // loop back
                            // now we know where to jump to (to exit the loop)
                            ref(code)[_b] = size(ref(code))
                        ]
    ;
```

statement grammar upgrade (3)

```
compound_statement =
    '{' >> -statement_list >> '}'
    ;

statement_ =
        var_decl
    |   assignment
    |   compound_statement
    |   if_statement
    |   while_statement
    ;

statement_list = +statement_;
```

The mini_c compiler

"I was once a calculator"

- Not a calculator anymore!
- Full fledged minimal C-like programming language
- Builds on top of calc7
- KISS: No types other than ints

The mini_c VM

```
op_stk_adj,     // adjust the stack (for args and locals)
op_call,        // function call
op_return       // return from function
```

```
int vmachine::execute(
    std::vector<int> const& code
  , std::vector<int>::const_iterator pc
  , std::vector<int>::iterator frame_ptr
)
{
    std::vector<int>::iterator stack_ptr = frame_ptr;

    while (true)
    {
        BOOST_ASSERT(pc != code.end());

        switch (*pc++)
        {
            /*...*/
        }
    }
}
```

```
case op_stk_adj:
    stack_ptr += *pc++;
    break;

case op_return:
    return stack_ptr[-1];
```

```
case op_call:
    {
        int nargs = *pc++;
        int jump = *pc++;

        // a function call is a recursive call to execute
        int r = execute(
            code
          , code.begin() + jump
          , stack_ptr - nargs
        );

        // cleanup after return from function
        stack_ptr[-nargs] = r;      //  get return value
        stack_ptr -= (nargs - 1);   //  the stack will now contain
                                    //  the return value
    }
    break;
```

The mini_c skipper grammar

```
template <typename Iterator>
struct white_space : grammar<Iterator>
{
    white_space()
    {
        start =
                space                                  // tab/space/cr/lf
            |   "/*" >> *(char_ - "*/") >> "*/"        // C-style comments
            ;
    }

    rule<Iterator> start;
};
```

The mini_c expression grammar functions!:

```
typedef white_space<Iterator> white_space;
rule<Iterator, locals<function_info, int>, white_space> function_call;
symbols<char, function_info>& functions;
```

```
struct function_info
{
    int arity;
    int address;
};
```

The mini_c expression grammar function call:

```
typedef white_space<Iterator> white_space;
rule<Iterator, locals<function_info, int>, white_space> function_call;
symbols<char, function_info>& functions;
```

```
function_call =
    functions                               [_a = _1]
    >>  '('
    >> -(
            expr                            [++_b]
            >> *(',' > expr                 [++_b])
        )
    >   char_(')')                          [op(_a, _b, pass)]
    ;
```

The mini_c expression grammar functions call:

```
// special overload for function calls
void operator()(
    function_info const& info, int got_nargs, bool& parse_result) const
{
    if (got_nargs == info.arity)
    {
        code.push_back(op_call);
        code.push_back(info.arity);
        code.push_back(info.address);
    }
    else
    {
        parse_result = false; // fail the parse
        std::cerr << "wrong number of args" << std::endl;
    }
}
```

The mini_c statement grammar functions return:

- `symbols<char, function_info>& functions;`
- `int nvars;`
- `bool has_return;`

- `rule<Iterator, white_space> return_statement;`

```
return_statement =
        lexeme[
            "return"
            >> !(alnum | '_') // make sure we have whole words
        ]
    >> -(
            eps(ref(has_return)) > expr     [op(op_return)]
        )
    >   ';'
    ;
```

The mini_c program grammar

```
template <typename Iterator>
struct program : grammar<Iterator, grammar<white_space_def<Iterator> > >
{
    program(std::vector<int>& code);

    typedef white_space<Iterator> white_space;

    std::vector<int>& code;
    rule<Iterator, std::string(), white_space> identifier;
    rule<Iterator, white_space> start;

    typedef
        locals<
            std::string // function name
          , int         // address
        >
    function_locals;

    symbols<char, function_info> functions;
    statement<Iterator> statement_def;
    grammar<statement<Iterator> > statement;

    rule<Iterator, function_locals, white_space> function;
    boost::phoenix::function<function_adder> add_function;
    boost::phoenix::function<function_state_reset> state_reset;
    boost::phoenix::function<compile_op> op;
};
```

```
typedef
    locals<
        std::string // function name
      , int         // address
    >
function_locals;

symbols<char, function_info> functions;
statement<Iterator> statement;

rule<Iterator, function_locals, white_space> function;
boost::phoenix::function<function_adder> add_function;
boost::phoenix::function<function_state_reset> state_reset;
boost::phoenix::function<compile_op> op;
```

```
function =
        (
            lit("void")                 [ref(has_return) = false]
        |   lit("int")                  [ref(has_return) = true]
        )
    >>  !functions                      // no duplicate functions!
    >>  identifier                      [_a = _1]
    >>  '('
    >  -(
            identifier                  [add_var(_1)]
            >> *(',' > identifier       [add_var(_1)])
        )
    >   ')'
    >   char_('{')                      [
                                            _b = size(ref(code)),
                                            add_function(
                                                _a     // function name
                                              , ref(nvars)      // arity
                                              , size(ref(code)) // address
                                            ),
                                            op(op_stk_adj, 0)   // adjust this later
                                        ]
    >   statement
    >   char_('}')                      [state_reset(_b)]
    ;
```

```
function =
        (
            lit("void")                     [ref(has_return) = false]
        |   lit("int")                      [ref(has_return) = true]
        )
    >>  !functions                          // no duplicate functions!
    >>  identifier                          [_a = _1]
    >>  '('
    >  -(
            identifier                      [add_var(_1)]
            >> *(',' > identifier           [add_var(_1)])
        )
    >   ')'
```

```
>   char_('{')                  [
                                    _b = size(ref(code)),
                                    add_function(
                                    _a     // function name
                                      , ref(nvars)      // arity
                                      , size(ref(code)) // address
                                    ),
                                    op(op_stk_adj, 0)   // adjust this later
                                 ]
>   statement
>   char_('}')                   [state_reset(_b)]
;
```

That’s it! ;-)

mini_c sample

```
/* My first mini program */

int pow2(n)
{
    int a = 2;
    int i = 1;
    while (i < n)
    {
        a = a * 2;
        i = i + 1;
    }
    return a;
}

int main()
{
    return pow2(10);
}
```

Another mini_c sample

```
/* The factorial */

int factorial(n)
{
    if (n <= 0)
        return 1;
    else
        return n * factorial(n-1);
}

int main(n)
{
    return factorial(n);
}
```

Spirit.Karma

Generator Library

Karma (Sanskrit: कर्म: act, action, performance) is the concept of "action" or "deed" in Indian religions understood as that which causes the entire cycle of cause and effect.

Output generation

- Karma is a library for flexible generation of arbitrary character (byte) sequences
  - Based on the idea, that a grammar usable to parse an input sequence may as well be used to generate the very same sequence in the output
  - For parsing of some input most programmers use hand written code or parser generator tools
  - Need similar tools: ‘unparser generators’

- Karma is such a tool
  - Inspired by the StringTemplate library (ANTLR)
  - Allows strict model-view separation (Separation of format and data)
  - Defines a DSEL (domain specific embedded language) allowing to specify the structure of the output to generate in a language derived from PEG

"If standard IO-streams are a step towards the future, I sure hope the future will have a definitive solution for the Carpal Tunnel Syndrome."

-- Andrei Alexandrescu, CUJ Aug. 2005

What's wrong with IOStreams?

```
unsigned int i = 0xffff;

// This prints: "***    0xffff***65535***"
std::printf("***%#10x***%u***", i, i);

// The equivalent using C++ IOStreams ...
std::ios_base::fmtflags f = std::cout.flags();
std::cout << "***"
          << std::showbase
          << std::setw(10)
          << std::hex
          << i;
std::cout.flags(f);
std::cout << "***"
          << i
          << "***";
```

What's wrong with IOStreams?

	printf	IOStreams
Type-safe	✗	✓
Extensible	✗	✓
Concise	✓	✗
Efficient	✓	✗
Separation of format from data	✓	✗

What's wrong with IOStreams?

```
unsigned int i = 0xffff;

// This prints: "***    0xffff***65535***"
std::cout <<
    karma::format(
        "***" << right_align(10)[hex] << "***" << uint_ << "***",
        i, i);
```

Output Generation

- Karma is the Yang to Qi's Yin
  - Everything you know about Qi's parsers is still true but has to be applied upside down (or inside out)

- Qi is all about *input* data conversion, Karma is about converting and formatting data for *output*.
- Qi gets input from *input iterators*, Karma outputs the generated data using an *output iterator*
- Qi uses `operator>>()`, Karma uses `operator<<()`
- Qi's semantic actions are called *after* a match and *receive* a value, Karma's semantic actions are called *before* generating and *provide* one
- Qi's parser attributes are passed *up*, Karma's attributes are passed *down*

Comparison Qi/Karma

<table>
<tr><th></th><th>Qi</th><th>Karma</th></tr>
<tr><td>Main component</td><td>parser</td><td>generator</td></tr>
<tr><td>Main routine</td><td>parse(), match()</td><td>generate(), format()</td></tr>
<tr><td>Primitive components</td><td>• int_, char_, double_, …
• bin, oct, hex
• byte, word, dword, qword, …
• stream</td><td>• int_, char_, double_, …
• bin, oct, hex
• byte, word, dword, qword, pad, …
• stream</td></tr>
<tr><td>Non-terminals</td><td>• rule, grammar</td><td>• rule, grammar</td></tr>
<tr><td>Operators</td><td>• * (kleene)
• + (one or more)
• - (optional)
• % (list)
• >> (sequence)
• | (alternative)
• &, ! (predicates/eps)</td><td>• * (kleene)
• + (one or more)
• - (optional)
• % (list)
• << (sequence)
• | (alternative)
• &, ! (predicates/eps)</td></tr>
<tr><td>Directives</td><td>• lexeme[], skip[], omit[], raw[]
• nocase[]</td><td>• verbatim[], delimit[]
• left_align[], center[], right_align[]
• upper[], lower[]</td></tr>
</table>

Comparison Qi/Karma

	Qi	Karma

Semantic Action	receives value
	`int_ [ ref(i) = _1 ]`
	`(char_ >> int_)`
	`   [ref(c) = _1, ref(i) = _2]`
		provides value
		`int_ [ _1 = ref(i) ]`
		`(char_ << int_)`
		`   [_1 = ref(c), _2 = ref(i)]`

Attributes	• Return type (attribute) of a parser component is the type of the values it generates, it must be convertible to the target type. • Attributes are propagated up. • Attributes are passed as non-const& • Parser components may not have target attribute value	• The attribute of a generator component is the type of the values it expects, i.e. the provided value must be convertible to this type. • Attributes are passed down. • Attributes are passed as const& • Generator components need always a ‚source‘ value: either literal or parameter

Output generation

- Domain specific embedded language (DSEL) was modeled after the PEG as used for parsing, i.e. set of rules describing what output is generated in what sequence:

```
int_(10) << lit("123") << char_('c')                // 10123c

(int_ << lit)[_1 = val(10), _2 = val("123")]        // 10123

vector<int> v = { 1, 2, 3 };
(*int_)[_1 = ref(v)]                                // 123

(int_ % ",") [_1 = ref(v)]                          // 1,2,3
```

Output Generation

- Three ways of associating data (values) with formating rules:
  - Using literals, direct association of values
    - `int_(10), char_('c')`
  - Explicit passing of values to API functions
    - Direct generator API (`generate()` family of functions)
    - Stream based generator API (`format()` functions)
  - Semantic actions, direct assignment of values
    - `int_[_1 = val(10)]`

The Direct Generator API

- Generating output without delimiters

```
int i = 42, j = 7;
generate(sink, int_, i);                // outputs: "42"
generate(sink, int_ << int_, i, j);   // outputs: "427"
```

- Generating output using delimiters

```
int i = 42, j = 7;
generate(sink, int_, space, i);       // outputs: "42 "
generate(sink, int_ << int_, space, i, j);
                                      // outputs: "42 7 "
```

The Stream based Generator API

- Generating output without delimiters

```
int i = 42, j = 7;
os << format(int_, i);                 // outputs: "42"
os << format(int_ << int_, i, j);      // outputs: "427"
```

- Generating output with delimiters

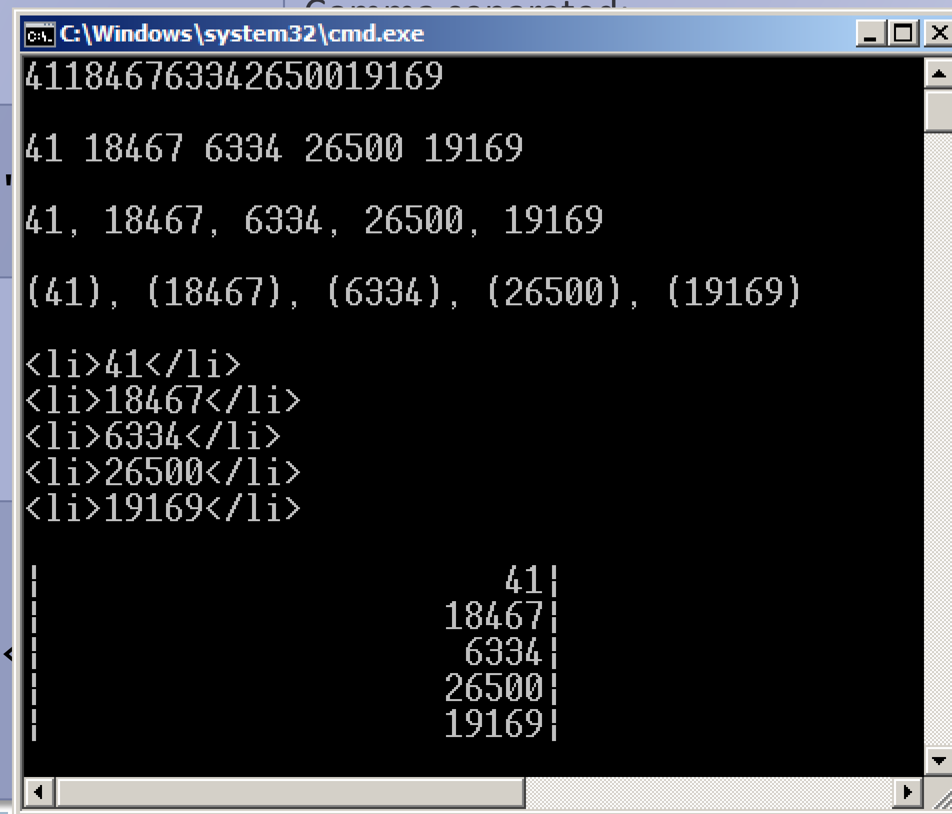
```
int i = 42, j = 7;
os << format_delimited(int_, i);       // outputs: " 42"
os << format_delimited(int_ << int_, i, j);
                                       // outputs: " 42 7"
```

Generator Types and their Attributes

	Karma generator types	AttributeType
Literals	• 'a', "abc", double_(1.0)	• No attribute
Primitive components	• int_, char_, double_, … • bin, oct, hex • byte, word, dword, qword, … • stream	• int, char, double, … • int • uint8_t, uint16_t, uint32_t, uint64_t • boost::any
Non-terminals	• rule<A()>, grammar<A()>	• Explicitely specified (A)
Operators	• *a (kleene) • +a (one or more) • -a (optional) • a % b (list) • a << b (sequence) • a | b (alternative)	• std::vector<A> (std container) • std::vector<A> (std container) • boost::optional<A> • std::vector<A> (std container) • fusion::vector<A, B> (sequence) • boost::variant<A, B>
Directives	• verbatim[a], delimit(…)[a] • lower[a], upper[a] • left_align[a], center[a], right_align[a]	• A • A • A
Semantic action	• a[f]	• A

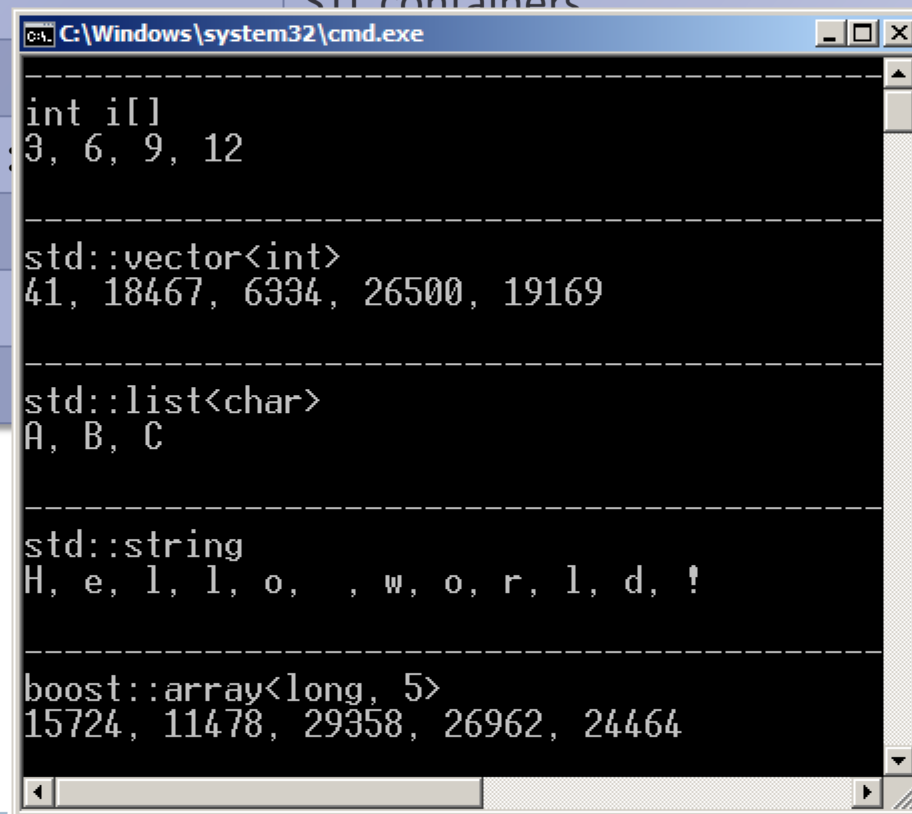
Different Output Grammars

Different output formats for:	std::vector<int>
'[' << *int_ << ']'	Without any separation: [12345]
'[' << (int_ % ", ") << ']'	Comma separated:
('(' << int_ << ')') % ", '	
*(" " << int_ << " ")	
*("|" << right_align[int_] <<	



Different Data Structures

Different data structures for:	stream % ", "
int i[4];	C style arrays
std::vector<int>	STL containers
std::list<char>	
std::vector<boost::gregorian:	
std::string, std::wstring	
boost::iterator_range<…>	
boost::array<long, 20>	



Formatting directives

- Alignment
  - Using spaces (default width: `BOOST_KARMA_DEFAULT_FIELD_LENGTH`):

```
left_align[…some generator…]
right_align[…some generator…]
center[…some generator…]

right_align[int_(12345)]                 // '     12345'
```

  - Using any generator, any width:

```
left_align(…)[…some generator…]
left_align(width, …)[…some generator…]

right_align(char_('*'))[int_(12345)]    // '*****12345'
right_align(6, char_('*'))[int_(12345)] // '*12345'
```

Formatting directives

- Switch between delimited and non-delimited modes

```
delimit[…some generator…]      // uses spaces
delimit(…)[…some generator…]   // uses given generator

verbatim[…some generator…]     // no delimiting

delimit[int_(12345)]                   // '12345 '
delimit(char_(','))[int_(12345)]       // '12345,'

vector<int> v = { 1, 2, 3 };
delimit(char_(','))[*int_]
    [_1 = ref(v)]                      // '1,2,3,'
```

Formatting directives

- Case management

```
upper_case[…some generator…]  // upper case
lower_case[…some generator…]  // lower case

// not only obvious conversions, but also
upper_case[double_(1.8e20)]   // 1.8E20
lower_case[double_(1.8e20)]   // 1.8e20

upper_case[hex(0xaBcD)]       // ABCD
lower_case[hex(0xaBcD)]       // abcd

// influences nan, inf as well (NAN, INF)
```

Semantic Actions

- Construct allowing to attach code to a generator component
  - Gets executed *before* the invocation of the generator
  - May *provide* values for the generators to output
  - May use local variables or rule arguments
- Syntax similar to parser semantic actions

```
int i = 4;
int_[_1 = ref(i)]
```

- Easiest way to write semantic actions is phoenix
  - `_1, _2,` … refer to elements of generator
  - `_a, _b,` … refer to locals (for `rule<>`'s)
  - `_r1, _r2,` … refer to arguments (for `rule<>`'s))
  - `pass` allows to make generator fail (by assigning false)

Semantic Actions

- Any function or function object can be called

```
void f(Attribute&, Context&, bool&);
void f(Attribute&, Context&);
void f(Attribute&);
void f();
```

- Attribute
  - Simple generator: just the attribute value
  - Compound generator: `fusion::vector<A1, A2, …>` (AN: attributes of generators)
- Context
  - Normally `unused_type` (except for `rule<>`'s and `grammar<>`'s, where this is a complex data structure)
  - Can be used to access rule's locals and attributes
- bool
  - Allows to make the generator fail (by assigning `false`)

Semantic Actions

- Plain function:

```
void read(int& i) { i = 42; }
int_[read]
```

- But it's possible to use `boost::lambda`...

```
using boost::lambda::_1;
int_[_1 = 42]
```

- ... and `boost::bind` as well

```
void read(int& i) { i = 42; }
int_[boost::bind(&read, _1)]
```

Doing something useful

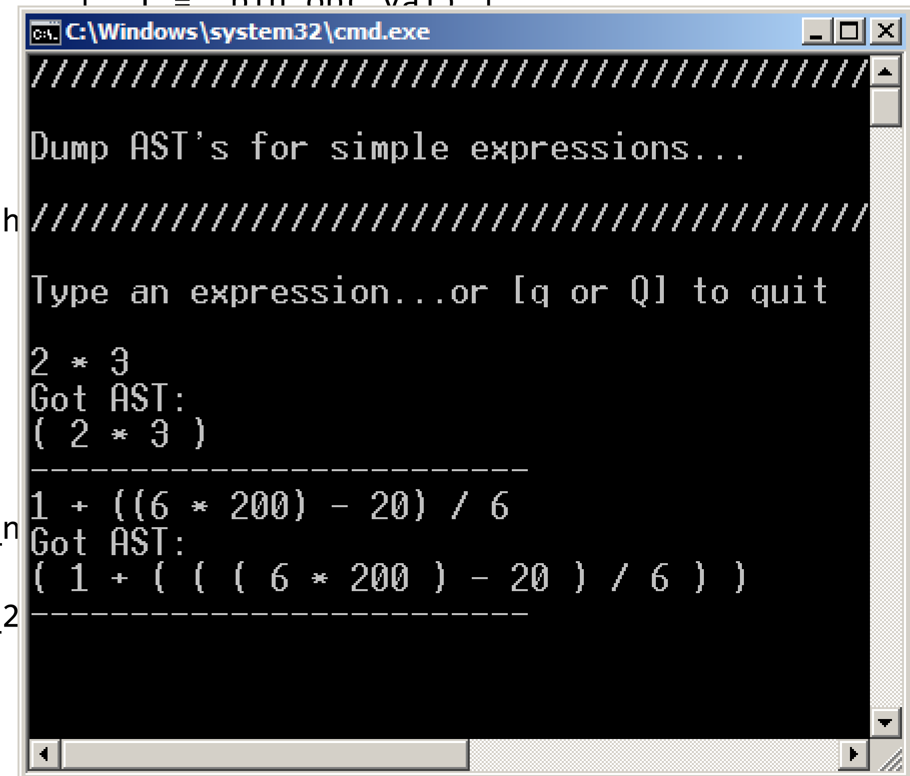
- Here is the AST again (still simplified):

```
// A node of the AST holds either an integer, a binary
// operation description, or a unary operation description
struct ast_node
{
    boost::variant<int, binary_op, unary_op> expr;
};

// For instance, a unary_op holds the description of the
// operation and a node of the AST
struct unary_op
{
    char op;              // '+' or '-'
    ast_node subject;
};
```

Doing something useful

- Output formatting using a grammar (printing infix expression):

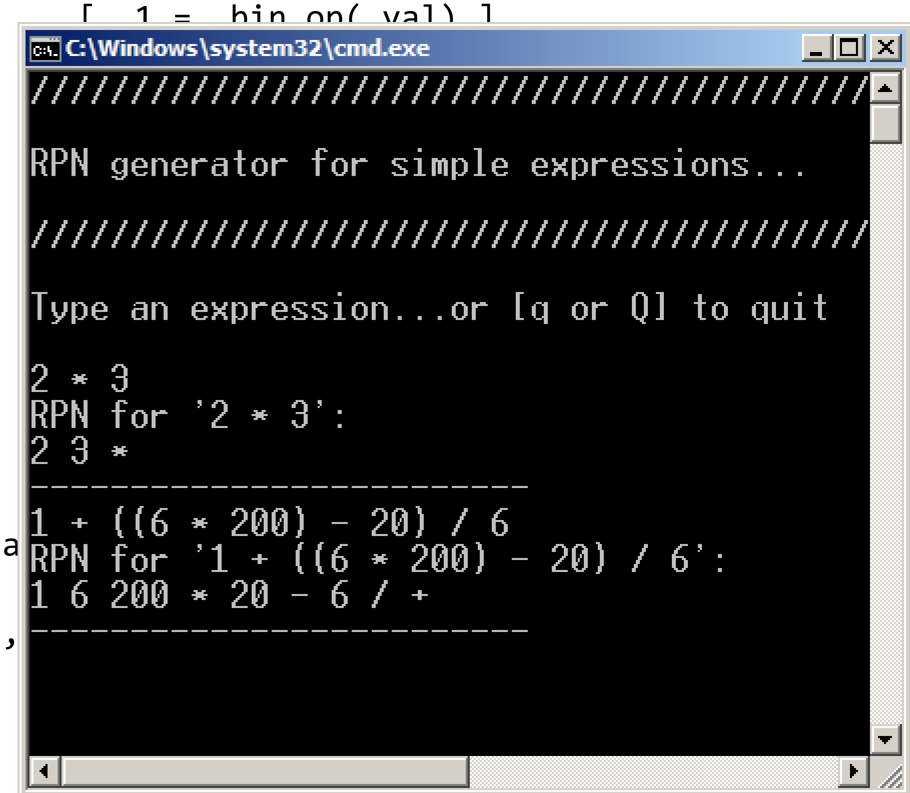
```
ast_node =
        int_                        [ _1 = _int(_val) ]
    |   binary_node                 [ _1 = bin_op(_val) ]
    |   unary_node
    ;

binary_node =
        ('(' << ast_node << ch
        [
            _1 = _left(_val),
        ]
    ;

unary_node =
        ('(' << char_ << ast_n
        [
            _1 = _op(_val), _2
        ]
    ;
```



Doing something useful

- Output formatting using a grammar (postfix expression):

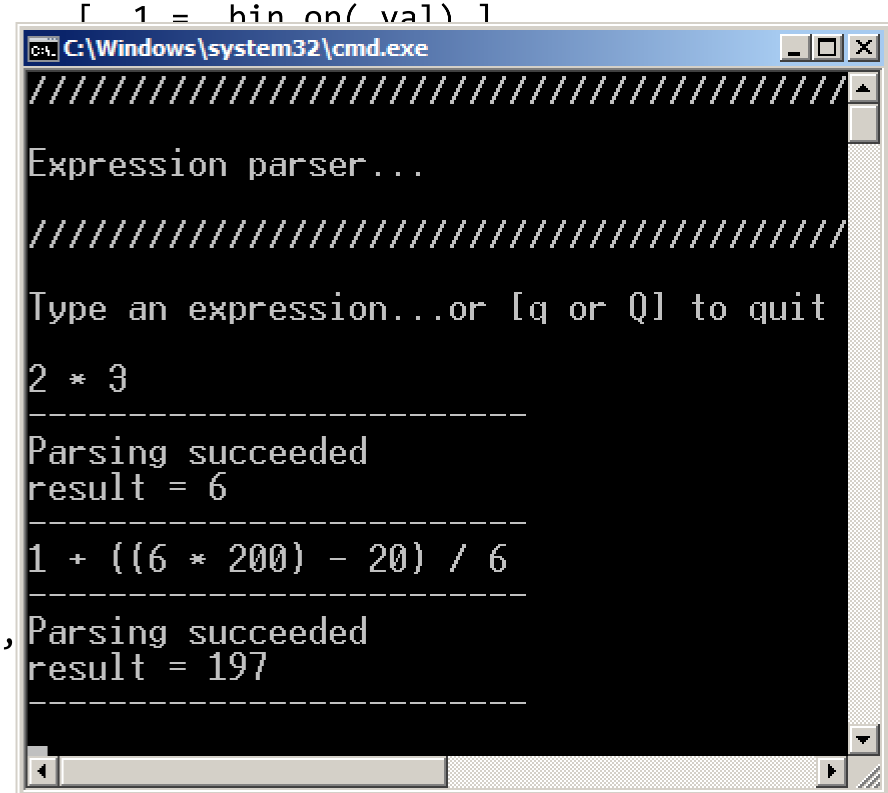
```
ast_node =
        int_                     [ _1 = _int(_val) ]
    |   binary_node              [ _1 = bin_op(_val) ]
    |   unary_node
    ;

binary_node =
        (ast_node << ast_node
        [
            _1 = _left(_val),
        ]
    ;

unary_node =
        '(' << ast_node << cha
        [
            _1 = _right(_val),
        ]
    ;
```



Doing something useful

- Output formatting using a grammar (byte code compiler):

```
ast_node =
        (dword(op_int) << dword) [ _1 = _int(_val) ]
    |   binary_node              [ _1 = _bin_op(_val) ]
    |   unary_node
    ;

binary_node =
        (ast_node << ast_node
        [
            _1 = _left(_val),
        ]
    ;

unary_node =
        (ast_node << byte)
        [
            _1 = _right(_val),
        ]
    ;
```



Conclusions

- Boost.Spirit is
  - A object oriented, recursive-descent parser and output generation library for C++
    - Versatile, usable in wide range of applications
    - Not a standalone tool, exposes embedded domain specific languages for parsing and output generation
    - Tightly integrated with target language
    - Allows for highly optimized code to be generated
  - For the first time PEG's are applied to output generation
  - While being implemented using heavy templated code and meta programming techniques, it exposes a simple and clean interface