1 Basic [atomicc.basic]

1.1 Introduction [atomicc.intro]

AtomicC is a structural hardware description language that extends C++ with Bluespec-style[1, 2, 3] modules, rules, interfaces, and methods. The compiler automatically synthesizes control signals that allow rules to fire only when their dependant elements are ready and when there are no conflicts with other rules executing in the same cycle. The removal of this analytic burden on the engineer increases productivity as well as improves reliability of the resulting design.

AtomicC is structural in that all state elements in the hardware netlist are explicit in the source code of the design. AtomicC is a timed HDL, using SystemC terminology. Atomic actions (rules and method invocations) execute in a single clock cycle. AtomicC does not attempt to replicate the behavior of all C++ constructs in hardware. Instead, it uses the C++ text to specify the necessary single static assignment(SSA) computations and performing these computations under an atomic rule-based execution model. In addition, an interface definition scheme is used to explicitly and flexibly manage the visibility of interface methods to a module.

Unlike C++'s serialized execution model, AtomicC allows all firing rules to be atomically executed on every clock cycle. The AtomicC compiler verifies that it is valid to consider all rules executed during a given clock cycle as if they were serialized into a linear, atomic ordering ("sequentially consistent"(SC)). Even though all concurrent rules are executed during the same clock cycle, SC allows us to compute the outcome of each rule independantly of any other rules that could be executing at the same time.

Like Connectal, AtomicC designs may include both hardware and software, using interfaces to specify hardware/software communication in a type safe way. The AtomicC compiler generates the code to pass arguments between hardware and software.

1.2 Compilation [atomicc.compilation]

AtomicC execution consists of 3 phases:

— netlist generation,

— netlist compilation or implementation

— and runtime.

During netlist generation, modules are instantiated by executing their constructors. During this phase, any C++ constructs may be used, but the resulting netlist may only contain synthesizeable components.

During netlist compilation, the netlist is analyzed and translated to an intermediate representation and then to Verilog for simulation or synthesis. Alternate translations are possible: to native code via LLVM, to System C, to Gallina for formal verification with the Coq Proof Assistant, etc.

1.3 Scheduling [atomicc.schedule]

Each rule has a set of state elements that it reads and another set of element that it writes. For the execution of a group of rules to be considered to be SC, the following must be true:

— Atomic: All operations for a given rule occur at the same point in the sequence.

— Read-before-write: A rule that writes a state element must occur later in the sequence than any rules that read the same state element.

— Non-conflicting: A given state element cannot be written by more than one concurrently executing rule.

The compiler and linker do not break SC violations automatically. Error require the user to annotate the source text with "priority" statements to resolve conflicts.

1.3.1 Definitions [atomicc.scheddefs]

— Rules: R_i

— Methods: M_i

— Control signals:

  — Exported signal(generated by callee): $ready(M_i)$

— Imported signal(generated by caller): $valid(M_i)$

— Rule firing condition: $\pi(M_i) \equiv ready(M_i)$ && $valid(M_i)$

— read set: $R_i.read$

— write set: $R_i.write$

— sensitivity set: $S(R_i) \equiv R_i.read \cup R_i.write$

— schedule set: all rules that could possibly conflict (rules that share elements in sensitivity set)

1.3.2 Algorithm [atomicc.schedalg]

```
// Partition rules into disjoint "schedule sets"
U = { R_i, M_i forall i }    // Construct set of unscheduled rules
While U ≠ ∅                  // While there are unscheduled rules
    Extract a rule, T, from U
    P_i = {T}                // Create next schedule set
    forall E in U
        if S(E) ∩ S(P_i) ≠ ∅
            Move E from U to P_i

forall P_i
    // Create 'read-before-write' graph
    Initialize graph G to have nodes for all elements in P_i
    forall T in P_i
        forall W in T.write
            forall J in P_i
                forall R in J.read
                    if W.name == R.name
                        add arc [T ⇒ J; guard: (W.cond && R.cond && π(T) && π(J))]
    // Check/repair 'read-before-write' graph to be SC
    forall loops L in G
       loopcondition = true
       forall arcs A in L
          loopcondition = loopcondition & A.guard
       if loopcondition is not identically false
          if loop has some method M_i and some rule R_j
              ready(R_j) = ready(R_j) && ¬π(M_i)
          else if source code has "priority R_i > R_j" & R_i in L & R_j in L
              ready(R_j) = ready(R_j) && ¬π(R_i)
          else
              loop still exists, report error
```

2 Classes [class]

2.1 Module declaration and definition [atomicc.module]

A module is defined using the keyword "___module", resulting in generation of a corresponding output verilog module. It includes local state elements, interfaces exported, interfaces imported and rules for clustering operations into atomic transactions.

Modules are independently compiled, even if they exist in the same compilation unit. Rule and interface method scheduling logic is generated as part of the generated module. Scheduling constraints (read set, write set and relation to other scheduled elements) are generated into a metadata file, allowing schedule consistency between modules to be verified by the linker.

[*Example*:

```
__module Echo {
    EchoRequest      request;              // exported interface
    EchoIndication   *indication;          // imported interface
    bool busy;
    __int(32) itemSay;
    ...
    // implementation of method request.say(). Note the guard "if (!busy)".
    void request.say(__int(32) v) if(!busy) {
        itemSay = v;
        ...
    }
    void request.saw(__int(16) a, __int(16) b) if(!busy) {
        ...
    }
};
```

— *end example*]

To reference a separately compiled module, use "___emodule". These external module definitions only need to include the exported/imported interfaces.

[*Example*:

```
__module EchoResponder {
    EchoIndication   indication;           // exported interface
};
```

— *end example*]

2.2 Module interface definition [atomicc.interface]

An AtomicC interface is essentially an abstract class similar to a Java interface. All the methods are virtual and no default implementations are provided. AtomicC style uses composition of interfaces rather than inheritance.

The ___interface keyword defines a list of methods that are exposed from an object. Instead of using object inheritance to define reusable interfaces, they are defined/exported explicitly by objects, allowing fine-grained specification of interface method visibility.

Methods of a module are translated to value ports for passing the method arguments and a pair of handshaking ports used for scheduling method invocations.

References to an object can only be done through interface methods. State element declarations inside an object (member variables) are private.

[*Example*:

```
__interface EchoRequest {
    void say(__int(32) v);
    void say2(__int(16) a, __int(16) b);
};
```

— *end example*]

2.3 Guard clauses on module interface methods [atomicc.guard]

1 Method definitions in ___module declarations have the form:

atomicc-method-definition:
decl-specifier-seq$_{opt}$ *interface-qualifier-seq identifier parameters-and-qualifiers function-body*

interface-qualifier:
identifier `.`

interface-qualifier-seq:
interface-qualifier
interface-qualifier-seq interface-qualifier

atomicc-function-body:
ctor-initializer$_{opt}$ *if-guard*$_{opt}$ *compound-statement*

if-guard:
`if (` *condition* `)`

Rules are only ready to fire if the rule's guard is true and all the guards on methods invoked within the rule are also true.

```
void request.say(__int(32) v) if(!busy) {
    itemSay = v;
    ...
}
```

2.4 Connecting exported interfaces to imported references [atomicc.connect]

The ___connect statement allows exported interface declarations to be connected with imported interface references between objects within a module declaration.

connect-declaration:
`__connect` *identifier* `=` *identifier* `;`

[*Example*:

```
__interface ExampleRequest {
    void say(__int(32) v);
};

__module A {
     ExampleRequest callIn;
};

__module B {
    ExampleRequest *callOut;
};

__module C {
    A consumer;
    B producer;
    __connect producer.callOut = consumer.callIn;
};
```

— *end example*]

Comparision with BSV:

— The declaration for 'A' is just like BSV. In BSV, the declaration for B requires the interface be passed in as an interface parameter (forcing a textual ordering to the source code declaration sequence).

— In AtomicC, the interfaces are stitched together outside in any convenient sequence in a location where both the concrete instances for A and B are visible.

2.5 Exporting interfaces from contained objects [atomicc.export]

In a design, there are times when the engineer wishes to declare an object locally, but allow external modules to access specific interfaces of the local object. This is done by declaring an interface to the containing object of compatible type and just 'assigning' the local object's interface to it.

[*Example*:

```
__module CWrapper {
    A consumer;
    ExampleRequest request = A.callIn;
 };
```

— *end example*]

CWrapper just forwards the interface 'request' down into the instance 'consumer'.

2.6 Syntax extension to C++ [atomicc.classsyn]

atomicc-class-key:

```
__interface
__emodule
__module
```

2.7 Exporting interfaces for use by software [atomicc.softif]

In systems that have both hardware and software components, there is a need to marshall/demarshall parameterized method invocations across a hardware bus or network-on-chip (NOC). AtomicC provides this with my decorating the interface declarations with the keyword "___software".

The use of the ___software keyword causes the following to be performed:

— The generation of serialization/deserialization code for both software and hardware side modules to allow the method invocations to be performed in each direction

— The generation of header files allowing compilation of software modules that interface with the hardware

— Integration into a modified Connectal execution framework for the orchestration of requests.

[*Example*:

```
__module Echo {
    __software EchoRequest      request;              // exported interface
    __software EchoIndication   *indication;          // imported interface
    bool busy;
    __int(32) itemSay;
    ...
    // implementation of method request.say(). Note the guard "if (!busy)".
    void request.say(__int(32) v) if(!busy) {
        itemSay = v;
        ...
    }
    void request.saw(__int(16) a, __int(16) b) if(!busy) {
        ...
    }
};
```

— *end example*]

[*Example*:

```
#include "EchoIndication.h"  // Header file generated by AtomicC
#include "EchoRequest.h"     // Header file generated by AtomicC

class EchoIndication : public EchoIndicationWrapper
{
public:
    virtual void heard(uint32_t v) {
        // user code for handling indication
    }
    EchoIndication(unsigned int id, PortalTransportFunctions *item, void *param) :
        EchoIndicationWrapper(id, item, param) {}
};

int main(int argc, const char **argv)
{
    EchoIndication echoIndication(IfcNames_EchoIndicationH2S, &transportMux, &param);
```

```
    EchoRequestProxy echoRequestProxy(IfcNames_EchoRequestS2H, &transportMux, &param);

    // user code for sending requests
    echoRequestProxy->say(42);
}
```

— *end example*]

3 Statements [stmt.stmt]

3.1 ___rule [atomicc.rule]

Rules specify a group of operations that must execute as an atomicly. A rule operates transactionally: when a rule's guard and the guards of all of its method invocations are satisfied, then it is ready to fire. It will fire on a clock cycle when it does not conflict with any higher priority rule.

rule-statement:
`__rule` *identifier* *if-guard*$_{opt}$ *compound-statement*

[*Example*:

```
__rule respond_rule if (responseAvail) {
    fifo->out.deq();
    ind->heard(fifo->out.first());
}
```

— *end example*]

4 Declarations [dcl.dcl]

4.1 bitstring [atomicc.bitdecl]

To declare a bitstring with or without sign extension.

bit-type-specifier:
`__uint (` *constant-expression* `)`
`__int (` *constant-expression* `)`

5 Expressions [expr]

5.1 Built-in functions [atomicc.builtin]

5.1.1 ___bitsize [atomicc.bitsize]

Function to return size in bits of a type or variable.

5.1.2 ___bitsubstr [atomicc.bitsubstr]

Function to return bit slice of bitstring

5.1.3 ___bitconcat [atomicc.bitconcat]

Function to bitstring that is the concatenation of all of the member values of the call.

5.2 ___bit_cast [atomicc.cast]

This can now be used to cast any datatype to/from ___int(A), allowing operations to be performed on a bit level.

atomic-bit-cast:
`__bit_cast <` *type-id* `> (` *expression* `)`

6 Modularization [atomicc.modularization]

6.1 Independant compilation of modules [atomicc.independant]

The design is separated into modules that can export and import interfaces to other modules. Each source language module compiles into a single verilog module. Modules are independantly compiled, depending only on the interface definitions for referenced modules. Referencing modules do not depend on the internal implementation of referenced modules, even if they textually exist in the same compilation unit. Scheduling of rules in a module is performed "inside out", with the resulting schedule dependancies written to a metadata file during compilation.

6.2 Execution control [atomicc.econtrol]

There are 2 common styles for communication of execution control information for a method:

— Asymmetric (ready/enable signalling) A method/rule is invoked by asserting the "enable" signal. This signal can only be asserted if the "ready" signal was valid, allowing the called module to restrict permissible execution sequences.

— Symmetric (ready/valid signalling) Both caller/callee have "able to be executed" signals. Execution is deemed to take place in each cycle where both "ready" (from the callee) and "valid" (from the caller) are asserted.

Bluespec uses the Asymmetric signalling style, collecting all scheduling control into a central location for analysis/generation. AtomicC uses the Symmetric signalling style, giving modules local control over their allowable execution patterns. Conflicts between local schedules for modules when they are connected together are detected by the linker.

6.3 Linking of groups of modules [atomicc.linker]

To verify that an instantiated group of modules has SC compliant execution characteristics, a linker is used to cross check information from the metadata files for each module.

6.4 Interfacing with verilog modules [atomicc.verilog]

To reference a module in verilog, fields can be declared in ___interface items.

[*Example*:

```
__interface CNCONNECTNET2 {
    __input  __int(1)         IN1;
    __input  __int(1)         IN2;
    __output __int(1)         OUT1;
    __output __int(1)         OUT2;
};
__emodule CONNECTNET2 {
    CNCONNECTNET2 _;
};
```

— *end example*]

This will allow references/instantiation of an externally defined verilog module CONNECTNET2 that has 2 'input' ports, IN1 and IN2, as well as 2 'output' ports, OUT1 and OUT2.

6.4.1 Parameterized modules [atomicc.param]

Verilog modules that have module instantiation parameters can also be declared/referenced.

[*Example*:

```
__interface Mmcme2MMCME2_ADV {
    __parameter const char *  BANDWIDTH;
    __parameter float         CLKFBOUT_MULT_F;
    __input  __uint(1)        CLKFBIN;
    __output __uint(1)        CLKFBOUT;
    __output __uint(1)        CLKFBOUTB;
```

```
};
__emodule MMCME2_ADV {
    Mmcme2MMCME2_ADV _;
};
```

— *end example*]

This example can be instantiated as:

[*Example*:

```
__module Test {
    ...
    MMCME2_ADV#(BANDWIDTH="WIDE",CLKFBOUT_MULT_F=1.0) mmcm;
    ...
    Test() {
       __rule initRule {
           mmcm._.CLKFBIN = mmcm._.CLKFBOUT;
       }
    }
}
```

— *end example*]

6.4.2 Reference syntax [atomicc.refsyntax]

atomicc-method-declaration:
attribute-specifier-seq$_{opt}$ *pin-type*$_{opt}$ *decl-specifier-seq*$_{opt}$ *member-declarator-list*$_{opt}$;

pin-type:
`__input`
`__output`
`__inout`
`__parameter`

[*Example*:

```
__interface <interfaceName> {
     __input __uint(1) executeMethod;
     __input __uint(16) methodArgument;
     __output __uint(1) methodReady;
}
```

— *end example*]

For '___parameter' items, supported datatypes include: "const char *", "float", "int".

Factoring of interfaces into sub interfaces is also supported.

6.4.3 Clock/reset ports [atomicc.clockReset]

Note that if interface port pins are declared in a module interface declaration, then CLK and nRST are _not_ automatically declared/instantiated. (Since the user needs the flexibility to not require them when interfacing with legacy code).

Note that this also allows arbitrary signals (like the output of clock generators) to be passed to modules as CLK/nRST signals. (For Atomicc generated modules, please note that the default clock/reset signals for a module will always have these names)

6.4.4 Import tooling [atomicc.itool]

There is a tool to automate the creation of AtomicC header files from verilog source files. [*Example*:

```
atomiccImport -o MMCME2_ADV.h -C MMCME2_ADV -P Mmcme2 zynq.lib
atomiccImport -o VMMCME2_ADV.h -C MMCME2_ADV -P Mmcme2 MMCME2_ADV.v
```

— *end example*]

7 Usage [atomicc.usage]

7.1 Command line switches [atomicc.command]

Command line switches...

7.2 debugging with printf [atomicc.printf]

To aid debugging with a simulator, "printf" statements in ___module declarations are translated to "$display" statements in the generated verilog. For debugging with synthesized hardware, "printf" statements are translated into indication packets sent through the NOC back to the software side host program. The format strings for the printf statements are placed into a generated file in generated/xxx.generated.printf along with a list of the bit lengths for each parameter to the printf.

printf-declaration:
```
__printf ;
```

To use the NOC printf:

— add the following line to the ___module being tested:

```
__printf;
```

— add a line similar to the following (with the 'xxx' replaced) to the test program:

```
atomiccPrintfInit("generated/rulec.generated.printf");
```

Annex A (informative) Grammar summary [agram]

[1] Summary of grammar.

A.1 Classes [agram.class]

atomicc-method-definition:
decl-specifier-seq$_{opt}$ *interface-qualifier-seq identifier parameters-and-qualifiers function-body*

interface-qualifier:
identifier `.`

interface-qualifier-seq:
interface-qualifier
interface-qualifier-seq interface-qualifier

atomicc-function-body:
ctor-initializer$_{opt}$ *if-guard*$_{opt}$ *compound-statement*

if-guard:
`if (` *condition* `)`

connect-declaration:
`__connect` *identifier* `=` *identifier* `;`

atomicc-class-key:
`__interface`
`__emodule`
`__module`

A.2 Statements [agram.stmt]

rule-statement:
`__rule` *identifier if-guard*$_{opt}$ *compound-statement*

A.3 Declarations [agram.dcl]

bit-type-specifier:
`__uint (` *constant-expression* `)`
`__int (` *constant-expression* `)`

A.4 Expressions [agram.expr]

atomic-bit-cast:
`__bit_cast <` *type-id* `> (` *expression* `)`

atomicc-method-declaration:
attribute-specifier-seq$_{opt}$ *pin-type*$_{opt}$ *decl-specifier-seq*$_{opt}$ *member-declarator-list*$_{opt}$ `;`

pin-type:
`__input`
`__output`
`__inout`
`__parameter`

printf-declaration:
`__printf ;`

Annex B (informative)
Scheduling examples [scheduleExample]

[1] Examples of how scheduling is computed

In the following examples, there are 3 rules: RuleA, RuleB and RuleC. There are 3 state elements: E1, E2 and E3.

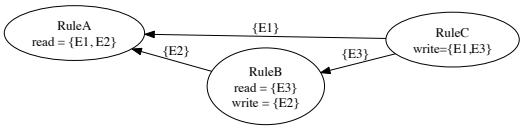

Figure 1 — Simple ordering example

A simple SC example is shown in Figure 1. The schedule sequence is A, B, C.

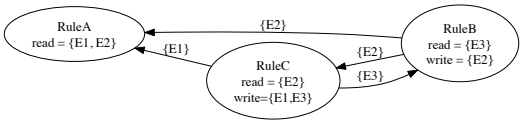

Figure 2 — non-SC ordering example

A non-SC example is shown in Figure 2. There is no linear sequence of the rules that preserves read-before-write for all state elements.

Annex C (informative)
Grammar integration with C++ summary [gram]

[1] Summary of C++ grammar

C.1 Keywords [gram.key]

[1] New context-dependent keywords are introduced into a program by `typedef` (**??**), `namespace` (**??**), class (Clause 2), enumeration (**??**), and `template` (**??**) declarations.

typedef-name:
identifier

namespace-name:
identifier
namespace-alias

namespace-alias:
identifier

class-name:
identifier
simple-template-id

enum-name:
identifier

template-name:
identifier

Note that a *typedef-name* naming a class is also a *class-name* (**??**).

C.2 Lexical conventions [gram.lex]

hex-quad:
hexadecimal-digit hexadecimal-digit hexadecimal-digit hexadecimal-digit

universal-character-name:
`\u` *hex-quad*
`\U` *hex-quad hex-quad*

preprocessing-token:
header-name
identifier
pp-number
character-literal
user-defined-character-literal
string-literal
user-defined-string-literal
preprocessing-op-or-punc
each non-white-space character that cannot be one of the above

token:
identifier
keyword
literal
operator
punctuator

header-name:
`<` *h-char-sequence* `>`
`"` *q-char-sequence* `"`

h-char-sequence:
h-char
h-char-sequence h-char

h-char:
any member of the source character set except new-line and `>`

q-char-sequence:
q-char
q-char-sequence q-char

q-char:
any member of the source character set except new-line and `"`

pp-number:
digit
`.` *digit*
pp-number digit
pp-number identifier-nondigit
pp-number `'` *digit*
pp-number `'` *nondigit*
pp-number `e` *sign*
pp-number `E` *sign*
pp-number `p` *sign*
pp-number `P` *sign*
pp-number `.`

identifier:
identifier-nondigit
identifier identifier-nondigit
identifier digit

identifier-nondigit:
nondigit
universal-character-name

nondigit: one of
```
a b c d e f g h i j k l m
n o p q r s t u v w x y z
A B C D E F G H I J K L M
N O P Q R S T U V W X Y Z _
```

digit: one of
```
0 1 2 3 4 5 6 7 8 9
```

preprocessing-op-or-punc: one of
```
{         }         [         ]         #         ##        (         )
<:        :>        <%        %>        %:        %:%:      ;         :         ...
new       delete    ?         ::        .         .*        ->        ->*       ~
!         +         -         *         /         %         ^         &         |
=         +=        -=        *=        /=        %=        ^=        &=        |=
==        !=        <         >         <=        >=        <=>       &&        ||
<<        >>        <<=       >>=       ++        --        ,
and       or        xor       not       bitand    bitor     compl
and_eq    or_eq     xor_eq    not_eq
```

literal:
integer-literal
character-literal
floating-literal
string-literal
boolean-literal
pointer-literal
user-defined-literal

integer-literal:
binary-literal integer-suffix$_{opt}$
octal-literal integer-suffix$_{opt}$
decimal-literal integer-suffix$_{opt}$
hexadecimal-literal integer-suffix$_{opt}$

binary-literal:
`0b` *binary-digit*
`0B` *binary-digit*
binary-literal `'`$_{opt}$ *binary-digit*

octal-literal:
`0`
octal-literal `'`$_{opt}$ *octal-digit*

decimal-literal:
nonzero-digit
decimal-literal `'`$_{opt}$ *digit*

hexadecimal-literal:
hexadecimal-prefix hexadecimal-digit-sequence

binary-digit: one of
`0 1`

octal-digit: one of
`0 1 2 3 4 5 6 7`

nonzero-digit: one of
`1 2 3 4 5 6 7 8 9`

hexadecimal-prefix: one of
`0x 0X`

hexadecimal-digit-sequence:
hexadecimal-digit
hexadecimal-digit-sequence `'`$_{opt}$ *hexadecimal-digit*

hexadecimal-digit: one of
`0 1 2 3 4 5 6 7 8 9`
`a b c d e f`
`A B C D E F`

integer-suffix:
unsigned-suffix long-suffix$_{opt}$
unsigned-suffix long-long-suffix$_{opt}$
long-suffix unsigned-suffix$_{opt}$
long-long-suffix unsigned-suffix$_{opt}$

unsigned-suffix: one of
`u U`

long-suffix: one of
`l L`

long-long-suffix: one of
`ll LL`

character-literal:
encoding-prefix$_{opt}$ `'` *c-char-sequence* `'`

encoding-prefix: one of
`u8 u U L`

c-char-sequence:
c-char
c-char-sequence c-char

c-char:
any member of the source character set except the single-quote `'`, backslash `\`, or new-line character
escape-sequence
universal-character-name

escape-sequence:
simple-escape-sequence
octal-escape-sequence
hexadecimal-escape-sequence

simple-escape-sequence: one of
`\'  \"  \?  \\`
`\a  \b  \f  \n  \r  \t  \v`

octal-escape-sequence:
    `\` *octal-digit*
    `\` *octal-digit octal-digit*
    `\` *octal-digit octal-digit octal-digit*

hexadecimal-escape-sequence:
    `\x` *hexadecimal-digit*
    hexadecimal-escape-sequence hexadecimal-digit

floating-literal:
    decimal-floating-literal
    hexadecimal-floating-literal

decimal-floating-literal:
    fractional-constant exponent-part$_{opt}$ *floating-suffix*$_{opt}$
    digit-sequence exponent-part floating-suffix$_{opt}$

hexadecimal-floating-literal:
    hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part floating-suffix$_{opt}$
    hexadecimal-prefix hexadecimal-digit-sequence binary-exponent-part floating-suffix$_{opt}$

fractional-constant:
    digit-sequence$_{opt}$ `.` *digit-sequence*
    digit-sequence `.`

hexadecimal-fractional-constant:
    hexadecimal-digit-sequence$_{opt}$ `.` *hexadecimal-digit-sequence*
    hexadecimal-digit-sequence `.`

exponent-part:
    `e` *sign*$_{opt}$ *digit-sequence*
    `E` *sign*$_{opt}$ *digit-sequence*

binary-exponent-part:
    `p` *sign*$_{opt}$ *digit-sequence*
    `P` *sign*$_{opt}$ *digit-sequence*

sign: one of
    `+ -`

digit-sequence:
    digit
    digit-sequence `'`$_{opt}$ *digit*

floating-suffix: one of
    `f l F L`

string-literal:
    encoding-prefix$_{opt}$ `"` *s-char-sequence*$_{opt}$ `"`
    encoding-prefix$_{opt}$ `R` *raw-string*

s-char-sequence:
    s-char
    s-char-sequence s-char

s-char:
    any member of the source character set except the double-quote `"`, backslash `\`, or new-line character
    escape-sequence
    universal-character-name

raw-string:
    `"` *d-char-sequence*$_{opt}$ `(` *r-char-sequence*$_{opt}$ `)` *d-char-sequence*$_{opt}$ `"`

r-char-sequence:
    r-char
    r-char-sequence r-char

r-char:
    any member of the source character set, except a right parenthesis `)` followed by
        the initial *d-char-sequence* (which may be empty) followed by a double quote `"`.

d-char-sequence:
    d-char
    d-char-sequence d-char

d-char:
any member of the basic source character set except:
space, the left parenthesis `(`, the right parenthesis `)`, the backslash `\`, and the control characters representing horizontal tab, vertical tab, form feed, and newline.

boolean-literal:
`false`
`true`

pointer-literal:
`nullptr`

user-defined-literal:
user-defined-integer-literal
user-defined-floating-literal
user-defined-string-literal
user-defined-character-literal

user-defined-integer-literal:
decimal-literal ud-suffix
octal-literal ud-suffix
hexadecimal-literal ud-suffix
binary-literal ud-suffix

user-defined-floating-literal:
fractional-constant exponent-part$_{opt}$ *ud-suffix*
digit-sequence exponent-part ud-suffix
hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part ud-suffix
hexadecimal-prefix hexadecimal-digit-sequence binary-exponent-part ud-suffix

user-defined-string-literal:
string-literal ud-suffix

user-defined-character-literal:
character-literal ud-suffix

ud-suffix:
identifier

C.3 Basics [gram.basic]

translation-unit:
declaration-seq$_{opt}$

C.4 Expressions [gram.expr]

primary-expression:
literal
`this`
`(` *expression* `)`
id-expression
lambda-expression
fold-expression
requires-expression

id-expression:
unqualified-id
qualified-id

unqualified-id:
identifier
operator-function-id
conversion-function-id
literal-operator-id
`~` *class-name*
`~` *decltype-specifier*
template-id

qualified-id:
nested-name-specifier `template`$_{opt}$ *unqualified-id*

nested-name-specifier:
`::`
type-name `::`
namespace-name `::`
decltype-specifier `::`
nested-name-specifier identifier `::`
nested-name-specifier `template`$_{opt}$ *simple-template-id* `::`

lambda-expression:
lambda-introducer compound-statement
lambda-introducer lambda-declarator requires-clause$_{opt}$ *compound-statement*
lambda-introducer `<` *template-parameter-list* `>` *requires-clause*$_{opt}$ *compound-statement*
lambda-introducer `<` *template-parameter-list* `>` *requires-clause*$_{opt}$
lambda-declarator requires-clause$_{opt}$ *compound-statement*

lambda-introducer:
`[` *lambda-capture*$_{opt}$ `]`

lambda-declarator:
`(` *parameter-declaration-clause* `)` *decl-specifier-seq*$_{opt}$
noexcept-specifier$_{opt}$ *attribute-specifier-seq*$_{opt}$ *trailing-return-type*$_{opt}$

lambda-capture:
capture-default
capture-list
capture-default `,` *capture-list*

capture-default:
`&`
`=`

capture-list:
capture
capture-list `,` *capture*

capture:
simple-capture `...`$_{opt}$
`...`$_{opt}$ *init-capture*

simple-capture:
identifier
`&` *identifier*
`this`
`* this`

init-capture:
identifier initializer
`&` *identifier initializer*

fold-expression:
`(` *cast-expression fold-operator* `...` `)`
`(` `...` *fold-operator cast-expression* `)`
`(` *cast-expression fold-operator* `...` *fold-operator cast-expression* `)`

fold-operator: one of
`+` `-` `*` `/` `%` `^` `&` `|` `<<` `>>`
`+=` `-=` `*=` `/=` `%=` `^=` `&=` `|=` `<<=` `>>=` `=`
`==` `!=` `<` `>` `<=` `>=` `&&` `||` `,` `.*` `->*`

requires-expression:
`requires` *requirement-parameter-list*$_{opt}$ *requirement-body*

requirement-parameter-list:
`(` *parameter-declaration-clause*$_{opt}$ `)`

requirement-body:
`{` *requirement-seq* `}`

requirement-seq:
requirement
requirement-seq requirement

requirement:
simple-requirement
type-requirement
compound-requirement
nested-requirement

simple-requirement:
expression `;`

type-requirement:
`typename` *nested-name-specifier*$_{opt}$ *type-name* `;`

compound-requirement:
`{` *expression* `}` `noexcept`$_{opt}$ *return-type-requirement*$_{opt}$ `;`

return-type-requirement:
trailing-return-type
`->` *cv-qualifier-seq*$_{opt}$ *constrained-parameter* *cv-qualifier-seq*$_{opt}$ *abstract-declarator*$_{opt}$

nested-requirement:
`requires` *constraint-expression* `;`

postfix-expression:
primary-expression
postfix-expression `[` *expr-or-braced-init-list* `]`
postfix-expression `(` *expression-list*$_{opt}$ `)`
simple-type-specifier `(` *expression-list*$_{opt}$ `)`
typename-specifier `(` *expression-list*$_{opt}$ `)`
simple-type-specifier braced-init-list
typename-specifier braced-init-list
postfix-expression `.` `template`$_{opt}$ *id-expression*
postfix-expression `->` `template`$_{opt}$ *id-expression*
postfix-expression `.` *pseudo-destructor-name*
postfix-expression `->` *pseudo-destructor-name*
postfix-expression `++`
postfix-expression `--`
`dynamic_cast` `<` *type-id* `>` `(` *expression* `)`
`static_cast` `<` *type-id* `>` `(` *expression* `)`
`reinterpret_cast` `<` *type-id* `>` `(` *expression* `)`
`const_cast` `<` *type-id* `>` `(` *expression* `)`
atomicc-bit-cast
`typeid` `(` *expression* `)`
`typeid` `(` *type-id* `)`

expression-list:
initializer-list

pseudo-destructor-name:
nested-name-specifier$_{opt}$ *type-name* `::` `~` *type-name*
nested-name-specifier `template` *simple-template-id* `::` `~` *type-name*
`~` *type-name*
`~` *decltype-specifier*

unary-expression:
postfix-expression
`++` *cast-expression*
`--` *cast-expression*
unary-operator cast-expression
`sizeof` *unary-expression*
`sizeof` `(` *type-id* `)`
`sizeof` `...` `(` *identifier* `)`
`alignof` `(` *type-id* `)`
noexcept-expression
new-expression
delete-expression

unary-operator: one of
`*` `&` `+` `-` `!` `~`

new-expression:
    ::$_{opt}$ **new** *new-placement*$_{opt}$ *new-type-id* *new-initializer*$_{opt}$
    ::$_{opt}$ **new** *new-placement*$_{opt}$ **(** *type-id* **)** *new-initializer*$_{opt}$

new-placement:
    (*expression-list* **)**

new-type-id:
    type-specifier-seq *new-declarator*$_{opt}$

new-declarator:
    ptr-operator *new-declarator*$_{opt}$
    noptr-new-declarator

noptr-new-declarator:
    [*expression* **]** *attribute-specifier-seq*$_{opt}$
    noptr-new-declarator **[** *constant-expression* **]** *attribute-specifier-seq*$_{opt}$

new-initializer:
    (*expression-list*$_{opt}$ **)**
    braced-init-list

delete-expression:
    ::$_{opt}$ **delete** *cast-expression*
    ::$_{opt}$ **delete [ ]** *cast-expression*

noexcept-expression:
    noexcept (*expression* **)**

cast-expression:
    unary-expression
    (*type-id* **)** *cast-expression*

pm-expression:
    cast-expression
    pm-expression **.*** *cast-expression*
    pm-expression **->*** *cast-expression*

multiplicative-expression:
    pm-expression
    multiplicative-expression ***** *pm-expression*
    multiplicative-expression **/** *pm-expression*
    multiplicative-expression **%** *pm-expression*

additive-expression:
    multiplicative-expression
    additive-expression **+** *multiplicative-expression*
    additive-expression **-** *multiplicative-expression*

shift-expression:
    additive-expression
    shift-expression **<<** *additive-expression*
    shift-expression **>>** *additive-expression*

compare-expression:
    shift-expression
    compare-expression **<=>** *shift-expression*

relational-expression:
    compare-expression
    relational-expression **<** *compare-expression*
    relational-expression **>** *compare-expression*
    relational-expression **<=** *compare-expression*
    relational-expression **>=** *compare-expression*

equality-expression:
    relational-expression
    equality-expression **==** *relational-expression*
    equality-expression **!=** *relational-expression*

and-expression:
    equality-expression
    and-expression **&** *equality-expression*

exclusive-or-expression:
and-expression
exclusive-or-expression `^` *and-expression*

inclusive-or-expression:
exclusive-or-expression
inclusive-or-expression `|` *exclusive-or-expression*

logical-and-expression:
inclusive-or-expression
logical-and-expression `&&` *inclusive-or-expression*

logical-or-expression:
logical-and-expression
logical-or-expression `||` *logical-and-expression*

conditional-expression:
logical-or-expression
logical-or-expression `?` *expression* `:` *assignment-expression*

throw-expression:
`throw` *assignment-expression*$_{opt}$

assignment-expression:
conditional-expression
logical-or-expression assignment-operator initializer-clause
throw-expression

assignment-operator: one of
`= *= /= %= += -= >>= <<= &= ^= |=`

expression:
assignment-expression
expression `,` *assignment-expression*

constant-expression:
conditional-expression

C.5 Statements [gram.stmt]

statement:
labeled-statement
attribute-specifier-seq$_{opt}$ *expression-statement*
attribute-specifier-seq$_{opt}$ *compound-statement*
attribute-specifier-seq$_{opt}$ *selection-statement*
attribute-specifier-seq$_{opt}$ *iteration-statement*
attribute-specifier-seq$_{opt}$ *jump-statement*
declaration-statement
attribute-specifier-seq$_{opt}$ *try-block*
rule-statement ■■

init-statement:
expression-statement
simple-declaration

condition:
expression
attribute-specifier-seq$_{opt}$ *decl-specifier-seq declarator brace-or-equal-initializer*

labeled-statement:
attribute-specifier-seq$_{opt}$ *identifier* `:` *statement*
attribute-specifier-seq$_{opt}$ `case` *constant-expression* `:` *statement*
attribute-specifier-seq$_{opt}$ `default` `:` *statement*

expression-statement:
expression$_{opt}$ `;`

compound-statement:
`{` *statement-seq*$_{opt}$ `}`

statement-seq:
statement
statement-seq statement

selection-statement:
`if constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *statement*
`if constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *statement* `else` *statement*
`switch (` *init-statement*$_{opt}$ *condition* `)` *statement*

iteration-statement:
`while (` *condition* `)` *statement*
`do` *statement* `while (` *expression* `) ;`
`for (` *init-statement condition*$_{opt}$ `;` *expression*$_{opt}$ `)` *statement*
`for (` *init-statement*$_{opt}$ *for-range-declaration* `:` *for-range-initializer* `)` *statement*

for-range-declaration:
attribute-specifier-seq$_{opt}$ *decl-specifier-seq declarator*
attribute-specifier-seq$_{opt}$ *decl-specifier-seq ref-qualifier*$_{opt}$ `[` *identifier-list* `]`

for-range-initializer:
expr-or-braced-init-list

jump-statement:
`break ;`
`continue ;`
`return` *expr-or-braced-init-list*$_{opt}$ `;`
`goto` *identifier* `;`

declaration-statement:
block-declaration

C.6 Declarations [gram.dcl]

declaration-seq:
declaration
declaration-seq declaration

declaration:
block-declaration
nodeclspec-function-declaration
function-definition
template-declaration
deduction-guide
explicit-instantiation
explicit-specialization
linkage-specification
namespace-definition
empty-declaration
attribute-declaration

block-declaration:
simple-declaration
asm-definition
namespace-alias-definition
using-declaration
using-directive
static_assert-declaration
alias-declaration
opaque-enum-declaration

nodeclspec-function-declaration:
attribute-specifier-seq$_{opt}$ *declarator* `;`

alias-declaration:
`using` *identifier attribute-specifier-seq*$_{opt}$ `=` *defining-type-id* `;`

simple-declaration:
decl-specifier-seq init-declarator-list$_{opt}$ `;`
attribute-specifier-seq decl-specifier-seq init-declarator-list `;`
attribute-specifier-seq$_{opt}$ *decl-specifier-seq ref-qualifier*$_{opt}$ `[` *identifier-list* `]` *initializer* `;`

static_assert-declaration:
`static_assert (` *constant-expression* `) ;`
`static_assert (` *constant-expression* `,` *string-literal* `) ;`

empty-declaration:
    `;`

attribute-declaration:
    attribute-specifier-seq `;`

decl-specifier:
    storage-class-specifier
    defining-type-specifier
    function-specifier
    `friend`
    `typedef`
    `constexpr`
    `inline`

decl-specifier-seq:
    decl-specifier attribute-specifier-seq$_{opt}$
    decl-specifier decl-specifier-seq

storage-class-specifier:
    `static`
    `thread_local`
    `extern`
    `mutable`

function-specifier:
    `virtual`
    explicit-specifier

explicit-specifier:
    `explicit (` *constant-expression* `)`
    `explicit`

typedef-name:
    identifier

type-specifier:
    simple-type-specifier
    elaborated-type-specifier
    typename-specifier
    cv-qualifier

type-specifier-seq:
    type-specifier attribute-specifier-seq$_{opt}$
    type-specifier type-specifier-seq

defining-type-specifier:
    type-specifier
    class-specifier
    enum-specifier

defining-type-specifier-seq:
    defining-type-specifier attribute-specifier-seq$_{opt}$
    defining-type-specifier defining-type-specifier-seq

simple-type-specifier:
nested-name-specifier$_{opt}$ *type-name*
nested-name-specifier `template` *simple-template-id*
nested-name-specifier$_{opt}$ *template-name*
`char`
`char16_t`
`char32_t`
`wchar_t`
`bool`
`short`
`int`
`long`
`signed`
`unsigned`
`float`
`double`
`void`
`auto`
decltype-specifier
bit-type-specifier

type-name:
class-name
enum-name
typedef-name
simple-template-id

decltype-specifier:
`decltype (` *expression* `)`
`decltype (` `auto` `)`

elaborated-type-specifier:
class-key attribute-specifier-seq$_{opt}$ *nested-name-specifier*$_{opt}$ *identifier*
class-key simple-template-id
class-key nested-name-specifier `template`$_{opt}$ *simple-template-id*
`enum` *nested-name-specifier*$_{opt}$ *identifier*

init-declarator-list:
init-declarator
init-declarator-list `,` *init-declarator*

init-declarator:
declarator initializer$_{opt}$
declarator requires-clause

declarator:
ptr-declarator
noptr-declarator parameters-and-qualifiers trailing-return-type

ptr-declarator:
noptr-declarator
ptr-operator ptr-declarator

noptr-declarator:
declarator-id attribute-specifier-seq$_{opt}$
noptr-declarator parameters-and-qualifiers
noptr-declarator `[` *constant-expression*$_{opt}$ `]` *attribute-specifier-seq*$_{opt}$
`(` *ptr-declarator* `)`

parameters-and-qualifiers:
`(` *parameter-declaration-clause* `)` *cv-qualifier-seq*$_{opt}$
ref-qualifier$_{opt}$ *noexcept-specifier*$_{opt}$ *attribute-specifier-seq*$_{opt}$

trailing-return-type:
`->` *type-id*

ptr-operator:
`*` *attribute-specifier-seq*$_{opt}$ *cv-qualifier-seq*$_{opt}$
`&` *attribute-specifier-seq*$_{opt}$
`&&` *attribute-specifier-seq*$_{opt}$
nested-name-specifier `*` *attribute-specifier-seq*$_{opt}$ *cv-qualifier-seq*$_{opt}$

cv-qualifier-seq:
cv-qualifier cv-qualifier-seq$_{opt}$

cv-qualifier:
`const`
`volatile`

ref-qualifier:
`&`
`&&`

declarator-id:
`...`$_{opt}$ *id-expression*

type-id:
type-specifier-seq abstract-declarator$_{opt}$

defining-type-id:
defining-type-specifier-seq abstract-declarator$_{opt}$

abstract-declarator:
ptr-abstract-declarator
noptr-abstract-declarator$_{opt}$ *parameters-and-qualifiers trailing-return-type*
abstract-pack-declarator

ptr-abstract-declarator:
noptr-abstract-declarator
ptr-operator ptr-abstract-declarator$_{opt}$

noptr-abstract-declarator:
noptr-abstract-declarator$_{opt}$ *parameters-and-qualifiers*
noptr-abstract-declarator$_{opt}$ `[` *constant-expression*$_{opt}$ `]` *attribute-specifier-seq*$_{opt}$
`(` *ptr-abstract-declarator* `)`

abstract-pack-declarator:
noptr-abstract-pack-declarator
ptr-operator abstract-pack-declarator

noptr-abstract-pack-declarator:
noptr-abstract-pack-declarator parameters-and-qualifiers
noptr-abstract-pack-declarator `[` *constant-expression*$_{opt}$ `]` *attribute-specifier-seq*$_{opt}$
`...`

parameter-declaration-clause:
parameter-declaration-list$_{opt}$ `...`$_{opt}$
parameter-declaration-list `,` `...`

parameter-declaration-list:
parameter-declaration
parameter-declaration-list `,` *parameter-declaration*

parameter-declaration:
attribute-specifier-seq$_{opt}$ *decl-specifier-seq declarator*
attribute-specifier-seq$_{opt}$ *decl-specifier-seq declarator* `=` *initializer-clause*
attribute-specifier-seq$_{opt}$ *decl-specifier-seq abstract-declarator*$_{opt}$
attribute-specifier-seq$_{opt}$ *decl-specifier-seq abstract-declarator*$_{opt}$ `=` *initializer-clause*

initializer:
brace-or-equal-initializer
`(` *expression-list* `)`

brace-or-equal-initializer:
`=` *initializer-clause*
braced-init-list

initializer-clause:
assignment-expression
braced-init-list

braced-init-list:
`{` *initializer-list* `,`$_{opt}$ `}`
`{` *designated-initializer-list* `,`$_{opt}$ `}`
`{ }`

initializer-list:
initializer-clause `...`$_{opt}$
initializer-list `,` *initializer-clause* `...`$_{opt}$

designated-initializer-list:
designated-initializer-clause
designated-initializer-list `,` *designated-initializer-clause*

designated-initializer-clause:
designator brace-or-equal-initializer

designator:
`.` *identifier*

expr-or-braced-init-list:
expression
braced-init-list

function-definition:
atomicc-method-definition ■■
attribute-specifier-seq$_{opt}$ *decl-specifier-seq*$_{opt}$ *declarator virt-specifier-seq*$_{opt}$ *function-body*
attribute-specifier-seq$_{opt}$ *decl-specifier-seq*$_{opt}$ *declarator requires-clause function-body*

function-body:
atomicc-function-body ■■
function-try-block
`= default ;`
`= delete ;`

enum-name:
identifier

enum-specifier:
enum-head `{` *enumerator-list*$_{opt}$ `}`
enum-head `{` *enumerator-list* `, }`

enum-head:
enum-key attribute-specifier-seq$_{opt}$ *enum-head-name*$_{opt}$ *enum-base*$_{opt}$

enum-head-name:
nested-name-specifier$_{opt}$ *identifier*

opaque-enum-declaration:
enum-key attribute-specifier-seq$_{opt}$ *nested-name-specifier*$_{opt}$ *identifier enum-base*$_{opt}$ `;`

enum-key:
`enum`
`enum class`
`enum struct`

enum-base:
`:` *type-specifier-seq*

enumerator-list:
enumerator-definition
enumerator-list `,` *enumerator-definition*

enumerator-definition:
enumerator
enumerator `=` *constant-expression*

enumerator:
identifier attribute-specifier-seq$_{opt}$

namespace-name:
identifier
namespace-alias

namespace-definition:
named-namespace-definition
unnamed-namespace-definition
nested-namespace-definition

named-namespace-definition:
`inline`$_{opt}$ `namespace` *attribute-specifier-seq*$_{opt}$ *identifier* `{` *namespace-body* `}`

unnamed-namespace-definition:
`inline`$_{opt}$ `namespace` *attribute-specifier-seq*$_{opt}$ `{` *namespace-body* `}`

nested-namespace-definition:
`namespace` *enclosing-namespace-specifier* `::` *identifier* `{` *namespace-body* `}`

enclosing-namespace-specifier:
identifier
enclosing-namespace-specifier `::` *identifier*

namespace-body:
declaration-seq$_{opt}$

namespace-alias:
identifier

namespace-alias-definition:
`namespace` *identifier* `=` *qualified-namespace-specifier* `;`

qualified-namespace-specifier:
nested-name-specifier$_{opt}$ *namespace-name*

using-directive:
attribute-specifier-seq$_{opt}$ `using namespace` *nested-name-specifier*$_{opt}$ *namespace-name* `;`

using-declaration:
`using` *using-declarator-list* `;`

using-declarator-list:
using-declarator `...`$_{opt}$
using-declarator-list `,` *using-declarator* `...`$_{opt}$

using-declarator:
`typename`$_{opt}$ *nested-name-specifier unqualified-id*

asm-definition:
attribute-specifier-seq$_{opt}$ `asm (` *string-literal* `) ;`

linkage-specification:
`extern` *string-literal* `{` *declaration-seq*$_{opt}$ `}`
`extern` *string-literal declaration*

attribute-specifier-seq:
attribute-specifier-seq$_{opt}$ *attribute-specifier*

attribute-specifier:
`[ [` *attribute-using-prefix*$_{opt}$ *attribute-list* `] ]`
contract-attribute-specifier
alignment-specifier

alignment-specifier:
`alignas (` *type-id* `...`$_{opt}$ `)`
`alignas (` *constant-expression* `...`$_{opt}$ `)`

attribute-using-prefix:
`using` *attribute-namespace* `:`

attribute-list:
attribute$_{opt}$
attribute-list `,` *attribute*$_{opt}$
attribute `...`
attribute-list `,` *attribute* `...`

attribute:
attribute-token attribute-argument-clause$_{opt}$

attribute-token:
identifier
attribute-scoped-token

attribute-scoped-token:
attribute-namespace `::` *identifier*

attribute-namespace:
identifier

attribute-argument-clause:
`(` *balanced-token-seq*$_{opt}$ `)`

balanced-token-seq:
balanced-token
balanced-token-seq balanced-token

balanced-token:
`(` *balanced-token-seq*$_{opt}$ `)`
`[` *balanced-token-seq*$_{opt}$ `]`
`{` *balanced-token-seq*$_{opt}$ `}`
any *token* other than a parenthesis, a bracket, or a brace

contract-attribute-specifier:
`[ [ expects` *contract-level*$_{opt}$ `:` *conditional-expression* `] ]`
`[ [ ensures` *contract-level*$_{opt}$ *identifier*$_{opt}$ `:` *conditional-expression* `] ]`
`[ [ assert` *contract-level*$_{opt}$ `:` *conditional-expression* `] ]`

contract-level:
`default`
`audit`
`axiom`

C.7 Classes [gram.class]

class-name:
identifier
simple-template-id

class-specifier:
class-head `{` *member-specification*$_{opt}$ `}`

class-head:
class-key attribute-specifier-seq$_{opt}$ *class-head-name class-virt-specifier*$_{opt}$ *base-clause*$_{opt}$
class-key attribute-specifier-seq$_{opt}$ *base-clause*$_{opt}$

class-head-name:
nested-name-specifier$_{opt}$ *class-name*

class-virt-specifier:
`final`

class-key:
`class`
`struct`
`union`
atomicc-class-key ■■

member-specification:
member-declaration member-specification$_{opt}$
access-specifier `:` *member-specification*$_{opt}$

member-declaration:
attribute-specifier-seq$_{opt}$ *decl-specifier-seq*$_{opt}$ *member-declarator-list*$_{opt}$ `;`
atomicc-method-declaration ■■
function-definition
using-declaration
static_assert-declaration
template-declaration
deduction-guide
alias-declaration
connect-declaration ■■
printf-declaration ■■
empty-declaration

member-declarator-list:
member-declarator
member-declarator-list , *member-declarator*

member-declarator:
declarator virt-specifier-seq$_{opt}$ *pure-specifier*$_{opt}$
declarator requires-clause
declarator brace-or-equal-initializer$_{opt}$
identifier$_{opt}$ *attribute-specifier-seq*$_{opt}$: *constant-expression brace-or-equal-initializer*$_{opt}$

virt-specifier-seq:
virt-specifier
virt-specifier-seq virt-specifier

virt-specifier:
`override`
`final`

pure-specifier:
`= 0`

conversion-function-id:
`operator` *conversion-type-id*

conversion-type-id:
type-specifier-seq conversion-declarator$_{opt}$

conversion-declarator:
ptr-operator conversion-declarator$_{opt}$

base-clause:
: *base-specifier-list*

base-specifier-list:
base-specifier ...$_{opt}$
base-specifier-list , *base-specifier* ...$_{opt}$

base-specifier:
attribute-specifier-seq$_{opt}$ *class-or-decltype*
attribute-specifier-seq$_{opt}$ `virtual` *access-specifier*$_{opt}$ *class-or-decltype*
attribute-specifier-seq$_{opt}$ *access-specifier* `virtual`$_{opt}$ *class-or-decltype*

class-or-decltype:
nested-name-specifier$_{opt}$ *class-name*
nested-name-specifier `template` *simple-template-id*
decltype-specifier

access-specifier:
`private`
`protected`
`public`

ctor-initializer:
: *mem-initializer-list*

mem-initializer-list:
mem-initializer ...$_{opt}$
mem-initializer-list , *mem-initializer* ...$_{opt}$

mem-initializer:
mem-initializer-id (*expression-list*$_{opt}$)
mem-initializer-id braced-init-list

mem-initializer-id:
class-or-decltype
identifier

C.8 Overloading [gram.over]

operator-function-id:
`operator` *operator*

operator: one of

```
new       delete    new[]     delete[]  ()        []        ->        ->*       ~
!         +         -         *         /         %         ^         &         |
=         +=        -=        *=        /=        %=        ^=        &=        |=
==        !=        <         >         <=        >=        <=>       &&        ||
<<        >>        <<=       >>=       ++        --        ,
```

literal-operator-id:
`operator` *string-literal identifier*
`operator` *user-defined-string-literal*

C.9 Templates [gram.temp]

template-declaration:
template-head declaration
template-head concept-definition

template-head:
`template` `<` *template-parameter-list* `>` *requires-clause*$_{opt}$

template-parameter-list:
template-parameter
template-parameter-list `,` *template-parameter*

requires-clause:
`requires` *constraint-logical-or-expression*

constraint-logical-or-expression:
constraint-logical-and-expression
constraint-logical-or-expression `||` *constraint-logical-and-expression*

constraint-logical-and-expression:
primary-expression
constraint-logical-and-expression `&&` *primary-expression*

concept-definition:
`concept` *concept-name* `=` *constraint-expression* `;`

concept-name:
identifier

template-parameter:
type-parameter
parameter-declaration
constrained-parameter

type-parameter:
type-parameter-key `...`$_{opt}$ *identifier*$_{opt}$
type-parameter-key identifier$_{opt}$ `=` *type-id*
template-head type-parameter-key `...`$_{opt}$ *identifier*$_{opt}$
template-head type-parameter-key identifier$_{opt}$ `=` *id-expression*

type-parameter-key:
`class`
`typename`

constrained-parameter:
qualified-concept-name `...` *identifier*$_{opt}$
qualified-concept-name identifier$_{opt}$ *default-template-argument*$_{opt}$

qualified-concept-name:
nested-name-specifier$_{opt}$ *concept-name*
nested-name-specifier$_{opt}$ *partial-concept-id*

partial-concept-id:
concept-name `<` *template-argument-list*$_{opt}$ `>`

default-template-argument:
`=` *type-id*
`=` *id-expression*
`=` *initializer-clause*

simple-template-id:
template-name `<` *template-argument-list*$_{opt}$ `>`

template-id:
simple-template-id
operator-function-id `<` *template-argument-list*$_{opt}$ `>`
literal-operator-id `<` *template-argument-list*$_{opt}$ `>`

template-name:
identifier

template-argument-list:
template-argument `...`$_{opt}$
template-argument-list `,` *template-argument* `...`$_{opt}$

template-argument:
constant-expression
type-id
id-expression

constraint-expression:
logical-or-expression

typename-specifier:
`typename` *nested-name-specifier identifier*
`typename` *nested-name-specifier* `template`$_{opt}$ *simple-template-id*

explicit-instantiation:
`extern`$_{opt}$ `template` *declaration*

explicit-specialization:
`template < >` *declaration*

deduction-guide:
`explicit`$_{opt}$ *template-name* `(` *parameter-declaration-clause* `) ->` *simple-template-id* `;`

C.10 Exception handling [gram.except]

try-block:
`try` *compound-statement handler-seq*

function-try-block:
`try` *ctor-initializer*$_{opt}$ *compound-statement handler-seq*

handler-seq:
handler handler-seq$_{opt}$

handler:
`catch (` *exception-declaration* `)` *compound-statement*

exception-declaration:
attribute-specifier-seq$_{opt}$ *type-specifier-seq declarator*
attribute-specifier-seq$_{opt}$ *type-specifier-seq abstract-declarator*$_{opt}$
`...`

noexcept-specifier:
`noexcept (` *constant-expression* `)`
`noexcept`

C.11 Preprocessing directives [gram.cpp]

preprocessing-file:
group$_{opt}$

group:
group-part
group group-part

group-part:
control-line
if-section
text-line
`#` *conditionally-supported-directive*

control-line:
`# include` *pp-tokens new-line*
`# define` *identifier replacement-list new-line*
`# define` *identifier lparen identifier-list*$_{opt}$ `)` *replacement-list new-line*
`# define` *identifier lparen* `...` `)` *replacement-list new-line*
`# define` *identifier lparen identifier-list* `,` `...` `)` *replacement-list new-line*
`# undef` *identifier new-line*
`# line` *pp-tokens new-line*
`# error` *pp-tokens*$_{opt}$ *new-line*
`# pragma` *pp-tokens*$_{opt}$ *new-line*
`#` *new-line*

if-section:
if-group elif-groups$_{opt}$ *else-group*$_{opt}$ *endif-line*

if-group:
`# if` *constant-expression new-line group*$_{opt}$
`# ifdef` *identifier new-line group*$_{opt}$
`# ifndef` *identifier new-line group*$_{opt}$

elif-groups:
elif-group
elif-groups elif-group

elif-group:
`# elif` *constant-expression new-line group*$_{opt}$

else-group:
`# else` *new-line group*$_{opt}$

endif-line:
`# endif` *new-line*

text-line:
pp-tokens$_{opt}$ *new-line*

conditionally-supported-directive:
pp-tokens new-line

lparen:
a `(` character not immediately preceded by white-space

identifier-list:
identifier
identifier-list `,` *identifier*

replacement-list:
pp-tokens$_{opt}$

pp-tokens:
preprocessing-token
pp-tokens preprocessing-token

new-line:
the new-line character

defined-macro-expression:
`defined` *identifier*
`defined (` *identifier* `)`

h-preprocessing-token:
any *preprocessing-token* other than `>`

h-pp-tokens:
h-preprocessing-token
h-pp-tokens h-preprocessing-token

has-include-expression:
`__has_include (` `<` *h-char-sequence* `>` `)`
`__has_include (` `"` *q-char-sequence* `"` `)`
`__has_include (` *string-literal* `)`
`__has_include (` `<` *h-pp-tokens* `>` `)`

has-attribute-expression:
`__has_cpp_attribute (` *pp-tokens* `)`

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