NVIDIA Material Definition Language 1.8

Language Specification

Document version 1.8.2
May 24, 2023

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Contents

1   Introduction

NVIDIA Material Definition Language (MDL) is a domain-specific language that describes the appearance of scene elements for a rendering process. MDL consists of a declarative component to describe materials as well as a procedural programming language to customize image texture lookups and procedural textures that provide the parametric input to the material declarations.

MDL is dedicated to providing an abstract material description that is well-defined and independent of particular rendering systems. The material description is comprehensive and flexible, yet specifically addresses modern renderers based on the simulation of physically based light transport. The declarative nature of the material description makes it easy for a renderer to fully understand a material, yet — if needed — to simplify and approximate the material to the best of the renderer's capabilities. The procedural programming language enables the aesthetic flexibility required by artists to design new materials.

Although it emphasizes physically plausible materials, MDL supports also traditional computer graphics techniques that are important in conventional rendering and modeling workflows, such as normal mapping and cut-outs.

MDL is designed for modern highly-parallel machine architectures. One important part is the declarative nature of the material description. Another part is its procedural language, which is restricted to the definition of pure functions, with access to the rendering state, that are free of side effects and global dependencies. Material and function evaluations can thus be easily compiled and executed on modern architectures.

1.1   Material building blocks

A material in MDL consists of a set of building blocks that describe how a renderer should compute the appearance of a geometrically described surface. A geometric surface is a mathematical idealization having no thickness that can only serve as a boundary between two volumes. Thus, the geometric definition of a sphere as a surface can instead be interpreted as the boundary of a spherically shaped volume.

MDL defines how light is affected by this boundary — reflected from the surface, refracted through the volume the surface defines, or a combination of both. The surface boundary can also define the extent of a medium through which the light passes and which participates in scattering and absorbing the light.

A geometric surface has no thickness. However, for the purposes of MDL, a surface can also be defined as having a thickness, though infinitesimally small. In MDL, this is said to be a *thin-walled* surface. The thin-walled property permits greater flexibility in defining the appearance of a surface that is not closed, and in which the surface is not the boundary of an object, but an object in itself. Because both sides of a thin-wall surface can be rendered, MDL also allows the two sides to possess different appearance properties.

Depending on the thin-walled property, MDL enables three categorically different materials with respect to how they interpret surfaces:

1. A surface is an interface between volumes. The volumetric properties defined in the material apply to the enclosed volume.

2. A surface represents a thin wall conceptually enclosing an infinitely thin volume with identical materials on both sides. Window glass, for example, can be modeled in this way.

3. A surface represents a thin wall with different materials on both sides, in which case both materials should have equal transmission interactions.

Material properties in MDL also include geometric properties of surfaces, such as cut-outs, displacements, or bump maps, which are commonly not modeled in the geometric description.

1.2 Material libraries and re-use of components

MDL has a well-defined module and package concept allowing for a comprehensive organization of complex material libraries. Together with the namespace concept, this allows for an easy deployment of material libraries from different providers that will still smoothly interoperate with future in-house material developments.

MDL modules contain materials and functions with their related types and constants. The re-use of those elements in MDL is important when building larger material libraries. Functions can be used to encapsulate other functions and change their signatures by changing their names, parameters, and return types and hiding details, such as unexposed parameters and their hidden settings. Materials can be used to encapsulate other materials, providing new names and parameters while, like functions, hiding unnecessary details.

1.3 Related documents

The document *NVIDIA Material Definition Language: Technical Introduction* illustrates the use of MDL through a series of images rendered using MDL materials and related code examples [1].

2 Terms and definitions

2.1 Typographical conventions

The grammar of many language elements is introduced at the beginning of a section using Wirth's extensions of Backus Normal Form. The left-hand side of a production is separated from the right hand side by a colon. Alternatives are separated by a vertical bar. Optional items are enclosed in square brackets. Curly braces indicate that the enclosed item may be repeated zero or more times.

Non-terminal and meta-symbols are given in *italic* font. Terminal symbols except identifiers, typenames, and literals are given in `teletype` font. See also Section 5 for the lexical structure of MDL.

For example:

struct_type_declaration	:	`struct` *simple_name* [*annotation_block*]
		`{` { *struct_field_declarator* } `}` `;`
struct_field_declarator	:	*type simple_name* [`=` *expression*]
		[*annotation_block*] `;`

2.2 File paths and resolution in the file system

MDL can reference external files with a string literal containing a *file path*. A string literal (see Section 5.8.5) used for file paths must not contain control codes (ASCII code < 32), delete (ASCII code 127), colon ':', and back slash '\'. Furthermore, the forward slash '/' is reserved as path separator, explained below, and cannot be used in file names or directory names.

A file path consists of a *file name*, optionally preceded by a *directory path* and a slash '/' as separator. A directory path consists of a sequence of *directory names* separated by slashes '/', optionally preceded by a single slash '/'.

An integration of MDL defines a sequence of *search paths*, whose order shall be consistent for all MDL file compilations. A search path is usually a file system path of a directory, but can be any directory location of a file-system-like hierarchy, for example, a network service for MDL modules or a data base. *File system paths* are used as a synonym for such generalized directory location in the following description.

Files referenced in MDL are always stored in the directory of a search path or below in subdirectories. File paths in MDL are not locations in the file system, but only references in relation to the search paths. The translation of a file path to a file system location is the *file resolution*, which takes the file path, the sequence of search paths, and the current working directory into account.

A reference to another file in MDL happens in an MDL module (see Section 15) . For all file resolutions inside a module, the directory containing this module is called the *current working directory*, whose file system path consists of the *current search path* followed by the *current module path*, where the path separator (slash '/') between the two shall be part of the current module path.

File paths beginning with a slash '/' are called *absolute file paths*. All other file paths are called *relative file paths*.

A single dot '.' as directory name can only be used at the beginning of a file path and only once. Two dots '..' as directory name can only be used at the beginning of a file path. It can be used more than once, but only as often as there are directories in the current module path, i.e., a sequence of two dots as directory names cannot be used to refer to any location above or outside the search paths. Other uses of these two special directory names are errors.

The file resolution proceeds in the following three steps:

1. Relative file paths are normalized to absolute file paths.

2. Absolute file paths are translated into file system locations using the search paths.

3. Final error conditions are checked.

For a relative file path, it is an error if this relative file path does not refer to a file relative to the current working directory. In this case, file resolution stops and reports that the file cannot be found.

A relative file path is normalized by prepending the relative file path with the current module path. Special directories are then normalized in the usual ways: a directory name of a single dot '.' is dropped, and a directory name of two dots '..' is dropped together with the matching regular directory name to its left.

The absolute file path is translated into a file system location by iterating through the sequence of search paths in their respective order until the file is found relative to the search path. If the file could not be located in any of the search paths, it is reported as not found.

The following additional error check safeguards MDL file references against possibly surprising behavior, namely that relative paths might refer to files in different search paths and not to a file, for example, in the same directory. This possible behavior is a consequence of the desirable property that a module in MDL is uniquely identified by its absolute file path, and therefore also all identifiers by their fully qualified name.

Check 1: Given a relative file path, it is an error if the file resolution finds a file in a different search path than the current search path. This condition describes a situation where the search path of the current module has a suitable file, but there exists a file of the same name and path in a higher prioritized search path and will thus take precedence; it shadows the file in the current search path.

This file resolution algorithm supersedes the one in MDL versions prior to MDL 1.6 irrespectively of the MDL versions in the involved MDL files with the exception of the following additional check.

Check 2: If the file path is a relative path that does not start with one of the special directories, i.e., the single dot '.' or two dots '..', and there is no file of that name relative to the current working directory, and the referring module has an MDL version of 1.5 or less, then file resolution starts again with the relative path changed to an absolute path by adding a slash '/' in front of it.

The following table lists example file paths and their respective file resolution results assuming the following example file structure with two search paths in the order as shown and assuming that the current module is the `test.mdl` module and of MDL version 1.6 or higher:

```
/search_path_1/a/x.mdl       // (1): file resolution finds this one first
              /a/b/y.mdl     // (2): file resolution finds this one first
              /a/b/w.mdl     // (3): not shadowing

/search_path_2/a/x.mdl       // (4): shadowed by module (1)
              /a/b/y.mdl     // (5): shadowed by module (2)
              /a/b/z.mdl     // (6): not shadowed
              /a/b/test.mdl // current module
```

File path	File resolution	Comment
`/a/x.mdl`	`/search_path_1/a/x.mdl`	file (1)
`../x.mdl`	<not found>	file (4) shadowed by (1), Check 1 fails
`/a/b/y.mdl`	`/search_path_1/a/b/y.mdl`	file (2), ignores file (5)
`y.mdl`	<not found>	file (5) shadowed by (2), Check 1 fails
`./y.mdl`	<not found>	file (5) shadowed by (2), Check 1 fails
`/a/b/z.mdl`	`/search_path_2/a/b/z.mdl`	file (6)
`z.mdl`	`/search_path_2/a/b/z.mdl`	file (6)
`./z.mdl`	`/search_path_2/a/b/z.mdl`	file (6)
`/a/b/w.mdl`	`/search_path_1/a/b/w.mdl`	file (3)
`w.mdl`	<not found>	file does not exist in `/search_path_2/a/b/`
`./w.mdl`	<not found>	file does not exist in `/search_path_2/a/b/`

In addition, if in this example the module `test.mdl` has an MDL version 1.5 or less, the following paths resolve successfully as follows, while they would all fail otherwise:

File path	File resolution	Comment
`a/x.mdl`	`/search_path_1/a/x.mdl`	file (1)
`a/b/y.mdl`	`/search_path_1/a/b/y.mdl`	file (2), ignores file (5)
`a/b/z.mdl`	`/search_path_2/a/b/z.mdl`	file (6)
`a/b/w.mdl`	`/search_path_1/a/b/w.mdl`	file (3)

Note 1: Relative file paths in an error-free MDL program can always be rewritten into an equivalent absolute file path referring to the same file.

Note 2: If a file path exists twice, each in a different search path, only the file in the first search path can be referenced in an error-free MDL program. This results in the desirable property of MDL that fully qualified names uniquely identify elements in the language independent of any context.

Note 3: Errors resulting from Check 1 can be fixed by referring to the higher prioritized file using an absolute file path.

Note 4: The use of the following characters in a file path can hinder cross platform portability of files: double quote '"', star '*', less than '<' , greater than '>', question mark '?', and pipe '|'.

Note 5: When upgrading an older module to MDL 1.6 or higher, a relative import path can fail with an error if it fulfills the conditions of Check 2 and it must be rewritten as an absolute import path to work correctly.

2.3   Texture files

A texture file can be referenced in MDL using a file path, as explained in Section 2.2. The file name shall end in one of the following file extensions, separated by a dot '.' from the base name, and the file shall be in the corresponding format.

Note: MDL integrations can support more texture file formats in the scene description and pass those textures into function or material parameters of suitable texture types.

Extension	File format
`png`	ISO/IEC 15948:2004 - Information technology — Computer graphics and image processing — Portable Network Graphics (PNG): Functional specification. Also as RFC 2083, PNG (Portable Network Graphics) Specification, Version 1.0, (March 1997).
`exr`	OpenEXR files understood by the SDK version 2.4, see https://www.openexr.com/
`jpg` `jpeg`	ISO/IEC 10918-1:1994, Digital Compression and Coding of Continuous-Tone Still Images. ISO/IEC CD 10918-5, Information technology – Digital compression and coding of continuous-tone still images: JPEG File Interchange Format (JFIF).
`ptx`	Ptex files understood by the SDK version 2.3.2, see https://ptex.us/
`vdb`	OpenVDB files understood by the SDK version 8.0, see https://www.openvdb.org/

Textures can optionally support channel or data set selection, uv-tilesets, and animation sequences, all explained in the following subsections.

2.3.1   Texture selector

Texture formats can support multiple data sets or channels in a file. They can be referenced with the string selector parameter of the `texture_2d` and `texture_3d` constructors in Section 6.14.1. The exact format for the string argument of the selector parameter is dependent on the file format and documented in this section.

In general, the selector values `"R"`, `"G"`, `"B"`, and `"A"` shall be supported to select the red, green, blue, or alpha channel, respectively, for texture formats that have conventional RGB, RGBA, and similar texel types.

If a file format supports multiple data sets, possibly with hierarchical naming, the selector uses the documented name format of the file format, optionally ending with the `"R"`, `"G"`, `"B"`, or `"A"` channel selector separated by a dot (`"."`). If there exists no naming standard, hierarchical names are concatenated with a dot (`"."`) as the separator.

The supported selectors for the standard texture formats are listed in the following table:

File format	Supported selector strings
PNG, JPEG	Depending on the texel type, `"R"`, `"G"`, `"B"`, and `"A"`.
OpenEXR	Part, nested layer, and channel names following the OpenEXR documentation. Examples: `"light1"`, or `"light1.specular.R"`.
OpenVDB	Grid name followed by an ordinal suffix and channel (all optional) following the OpenVDB grid documentation. Examples: `"density"`, `"density[0]"`, or `"[1].R"`.

2.3.2   Uv-tilesets

A texture file path in MDL can include one of the following *uv-tileset markers* in the filename. The texture reference refers then to a whole *uv-tileset*, a set of texture files used together as a single large two-dimensional texture. The different markers indicate the different filename conventions that encode where each texture file is placed in the *uv* texture space.

Marker	Pattern	(0,0)-index	Convention to format a (u, v)-index
`<UDIM>`	$\mathcal{DDDD}$	1001	UDIM, expands to the four digit number $1000 + (u + 1 + v * 10)$
`<UVTILE0>`	`"_u"`$\mathcal{I}$`"_v"`$\mathcal{I}$	`_u0_v0`	0-based uv-tileset, expands to `"_u"`u`"_v"`v
`<UVTILE1>`	`"_u"`$\mathcal{I}$`"_v"`$\mathcal{I}$	`_u1_v1`	1-based uv-tileset, expands to `"_u"`$(u + 1)$`"_v"`$(v + 1)$

A uv-tileset marker is replaced by its corresponding regular expression pattern from the table above to match all files that belong to this uv-tileset. The pattern uses the following abbreviations: `"text"` expands

to the literal `text`, $\mathcal{D}$ expands to one of the digits [0-9], and $\mathcal{I}$ expands to an integer number with an optional minus sign and optional leading zeros, i.e., [-]?[0-9]+.

The UDIM convention supports only non-negative indices and *u* needs to be less than ten. The 0-based and 1-based uv-tileset conventions do not restrict the value range of the indices. Optional leading zeros may cause multiple files to map to the same (u, v) index, which shall be reported as an error.

The following table shows example texture file paths and matching file names for the different conventions.

Example file path	Matching names for (u, v) index $(0, 0)$ and $(1, 0)$	
`example<UDIM>.png`	`example1001.png`	`example1002.png`
`example<UVTILE0>.png`	`example_u0_v0.png`	`example_u01_v00.png`
`example<UVTILE1>.png`	`example_u1_v1.png`	`example_u2_v01.png`

2.3.3 Texture sequences

A texture file path in MDL can include one *sequence marker* in the filename. Such a texture reference refers to a whole sequence of texture files, where each file represents a *frame* in the sequence. A frame is identified by a non-negative integer *frame number*.

The sequence marker consists of a non-empty list of '#' characters enclosed in angle brackets, for example, '<###>'. A frame number matches a sequence marker if it consists of at most as many digits as there are '#' characters in the sequence marker. The frame number may have leading zeros, which are ignored for the numerical interpretation of the frame number.

The *texture sequence* consists of all texture files that have a matching frame number in the place of the sequence marker. The sequence may have gaps. It is undefined behavior if a frame number occurs more than once, which can happen because of leading zeros.

The following table shows two sequences of matching texture file names for a texture sequence file path example.

Example file path	Matching file names			
`example<##>.png`	`example0.png`	`example1.png`	...	`example99.png`
`example<##>.png`	`example00.png`	`example01.png`	...	`example99.png`

2.4 Light profile files

A light profile file can be referenced in MDL using a file path, as explained in Section 2.2. The file name shall end in one of the following file extensions, separated by a dot '.' from the base name, and the file shall be in the corresponding format:

Extension	File format
`ies`	IES LM-63-02 Standard File Format for Electronic Transfer of Photometric Data and Related Information, Illuminating Engineering Society.

Note: MDL integrations can support more light profile file formats in the scene description and pass those into function or material parameters of a light profile type.

2.5 BSDF measurement data files

A bidirectional scattering distribution function (BSDF) measurement data file can be referenced in MDL using a file path, as explained in Section 2.2. The file name shall end in one of the following file extensions, separated by a dot '.' from the base name, and the file shall be in the corresponding format:

Extension	File format
`mbsdf`	MBSDF file format documented in Appendix B, Section 23.

Note: MDL integrations can support more BSDF measurement data file formats in the scene description and pass those into function or material parameters of a BSDF measurement type.

2.6 Quantities and units

Light transport simulation is performed in radiometric units. Material or function parameters may accept values in photometric units, but these values will eventually be converted to radiometric units before interacting with the renderer.

One of the most fundamental quantities in light transport is *radiance* leaving from (*exitant*) or arriving at (*incident*) a point x in direction ω. It is usually denoted by

$$L(x, \omega) \quad \left[\frac{W}{m^2 sr}\right]$$

and measured in watts per square meter per steradian. Note that exitant radiance usually differs strongly from incident radiance, because the former includes interaction of light with the local surface, while the latter does not.

Spectral rendering uses *spectral radiance* in $\left[W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}\right]$, which additionally depends on the wavelength in nanometers. The same applies to all following quantities. Radiance is obtained from spectral radiance by integrating over an interval of wavelengths. The integrand is commonly weighted by some kind of spectral response function.

The following sections follow conventional notation and omit the explicit reference to wavelength dependence for brevity.

Integrating incoming radiance L_i over a set of unit directions $\Omega \subseteq S^2$ around a point leads to *irradiance*

$$E(x) = \int_\Omega L_i(x, -\omega) d\bar{\sigma}(\omega) \quad \left[\frac{W}{m^2}\right],$$

where θ is the angle between the normal and ω, and

$$d\bar{\sigma}(\omega) = \begin{cases} d\sigma(\omega) & \text{in the volume,} \\ d\sigma^\perp(\omega) = |\cos\theta| \, d\sigma(\omega) & \text{on the surface.} \end{cases}$$

The measure $d\bar{\sigma}$ is simply a short-hand for the solid angle measure in the volume and the projected solid angle measure on the surface.

The similar integral of exitant radiance L_o, the radiance leaving a surface, is referred to as *radiant exitance* $M(x)$. This quantity is especially useful when describing light sources.

Finally, integrating irradiance (or radiant exitance) over surface area results in *power*

$$\Phi = \int_A E(x) dx \quad [W].$$

The unit used for distances depends on the context and can be *meters*, world space *scene units*, or implicit through some coordinate space transformation. Distances for the volume absorption coefficient and the volume scattering coefficient of the MDL material model in Section 13.3 are in meters in world space. The radius of the rounded corner state function in Section 19.3 is in meters in world space. Distances in internal space or object space can be transformed into scene units in world space using the coordinate space transformations in Section 19.2. Scene units can be multiplied with the result of the `::state::meters_per_scene_unit()` state function in Section 19.2 to convert them to meters. The `::state::scene_units_per_meter()` state function returns the reciprocal value.

Angles are specified in radians in the range from 0 to 2π, for example, as arguments to the trigonometric standard library functions. Rotations are specified in the range from 0 to 1, where 1 means a full rotation by an angle of 2π.

Note: Rotations can be used as function or material parameters that can be conveniently textured. This specification document makes currently no use of rotations.

3 Runtime model

MDL modules offer functions and materials for runtime execution. Both can have parameters that are provided with values at runtime. Besides parameters, state functions are used to communicate rendering state to the functions and materials defined in MDL.

3.1 Functions

Functions in MDL are conventional functions with input parameters and a return value. In addition, functions have read-only access to a runtime state through state functions. The runtime state provides standardized access to important values of the rendering context, such as the current position or texture coordinates.

An application integrating MDL can call functions at runtime with concrete arguments for the parameters and a runtime state. The function computes a return value to be used by the application.

More specifically, functions in MDL are pure in the sense of being side-effect free and are state-less in the sense that they always compute the same return value for the same argument values and runtime state.

Functions can be *overloaded*, in which the same name is used for more than one function, but where the functions differ in their parameter lists. Overload call resolution is explained in Section 12.4.

A relevant aspect of the MDL type system for the runtime integration is the handling of size-deferred arrays (see Section 7). Depending on the capabilities of the MDL integration, size-deferred arrays may not exist at runtime and overloaded functions are provided instead for each concrete array size used. This may imply that calling a function with a size-deferred array parameter requires a re-compilation of this function for the specific array size in the call. Calling the function again with a different array value, but of equal array size, should not require a re-compilation. Otherwise, the MDL design does not imply that a re-compilation would be necessary for other parameter types.

3.2 Materials

Materials in MDL consist of predefined building blocks with parameters that can be combined in flexible ways. The building blocks, their parameters and combinations are explained in the material model section (see Section 13).

The material building blocks have input parameters. These parameters can be set to literal values and the return value of function calls, including state function calls. The parameters to the function calls themselves can also be set to these types of values.

A material is instantiated when its input parameters are bound to specific values. This happens typically when a material is assigned to an object in the scene description. At instantiation, material input parameters can be set to literal values or the return value of function calls, including state function calls.

An application integrating MDL can instantiate materials and inspect material instances. Material inspection allows the application to understand the complete structure of how the material building blocks are combined and how all parameters of these building blocks are set. If a parameter is set to the return value of a function call, the application can retrieve the arguments provided to that function and call the function with the proper runtime state. The runtime state depends on the material building block where the function call result is needed.

Although material definitions cannot be overloaded in MDL, an MDL integration may choose to replace a material with parameters of size-deferred array types by a set of materials with concrete array sizes similar to how it may handle functions with size-deferred array parameter types.

3.3   Distance unit conversion between scene and MDL

Distances in MDL may expect their value in meters, world space scene units, or others defined by transformations. In particular the integration of scene units into MDL requires the runtime to know the ratio between a scene unit and a meter, for example, from an applications setting or a rendering option in the scene.

4   Overview

mdl	:	*mdl_version*
		{ *import* }
		[`module` *annotation_block* ;]
		{ [`export`] *global_declaration* }
mdl_version	:	`mdl` *floating_literal* ;
import	:	`import` *qualified_import* { , *qualified_import* } ;
	|	[`export`] `using` *import_path*
		`import` (* | *simple_name* { , *simple_name* }) ;
qualified_import	:	*import_path* `::` (* | *simple_name*)
qualified_name	:	[[`::`] *module_name* `::`] *simple_name*
simple_name	:	*IDENT*
global_declaration	:	*annotation_declaration*
	|	*constant_declaration*
	|	*type_declaration*
	|	*function_declaration*

A compilation unit in Material Definition Language (MDL) is a module. A module consists of a mandatory MDL version declaration, a sequence of using alias declarations and import declarations, an optional annotations block, and a sequence of global declarations. Imported elements as well as those from the global declarations can be exported to be used outside of the module itself in other modules or by a renderer.

4.1   MDL version declaration

Each MDL module starts with an MDL version declaration, only preceded by optional white space or comments. The version declaration identifies the module as written in the corresponding MDL version. The version itself consists of the major version number followed by a dot and the minor version number.

The following example illustrates how an MDL module can start that follows the version of this specification document:

    mdl 1.8;

4.2   Import declarations

In MDL, all identifiers and all typenames live in modules with the exception of the types available as built-in reserved words. A module defines a namespace and shields identifiers from naming conflicts. Modules can be used as such or they can be organized in packages, which define a namespace as well and nest the module namespace or sub-package namespace within their own. Modules and packages are explained in detail in Section 15.

Declarations inside a module need to be marked for export before they can be used outside of the module, and other modules need to import those declarations before they can be used.

Import declarations can import individual declarations or all declarations from other modules. Depending on the particular form of the import declarations used, the imported declarations can only be referred to by their qualified identifiers or by their unqualified identifiers. A qualified identifier includes the module and

package names as namespace prefixes separated by the scope operator ': :'. See Section 15.1 for the details of import declarations.

Modules implemented using different versions of MDL can be freely mixed with one restriction: Declarations that are not legal in a module's version of MDL cannot be imported from another module even though the declaration would be legal in that module's version of MDL. In other words, a module can only see declarations of other modules that are legal in its version of MDL. Details are explained in Section 15.4.

MDL's import mechanism does not offer any name-conflict resolution mechanisms, i.e., an identifier or type can only be imported in the unqualified form from one module. The purpose of this policy is to have a well-defined module system that enables packaging and re-use of material libraries by independent providers.

4.3   Global declarations

Global declarations can be any of:

- global constants, see Section 6.8,

- type declarations in the form of structure type declarations, see Section 8, enumeration type declarations, see Section 9, or typedef declarations, see Section 10,

- function declarations, Section 12,

- material definitions, Section 13, that are syntactically similar to function declarations and represented this way in the grammar, and

- annotation declarations, see Section 14.

Note: MDL does not have global variables (besides global constants) nor global material instances. The instancing of materials with concrete parameter values is left to the integration with the renderer or scene graph representation.

5 Lexical structure

This section describes the lexical structure of MDL.

5.1 Character set

An MDL source file is a sequence of characters from a character set. This set comprises at least the following characters:

1. the 52 uppercase and lowercase alphabetic characters:

   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

2. the 10 decimal digits:

   0 1 2 3 4 5 6 7 8 9

3. the blank or space character

4. the 32 graphic characters:

Character	Name	Character	Name
!	exclamation point	"	double quote
#	number sign	$	dollar sign
%	percent	&	ampersand
'	single quote	(	left parenthesis
)	right parenthesis	*	asterisk
+	plus	,	comma
−	hyphen or minus	.	period
/	slash	:	colon
;	semicolon	<	less than
=	equal	>	greater than
?	question mark	@	at symbol
[	left bracket	\	backslash
]	right bracket	^	circumflex
_	underscore	'	backquote
{	left brace	|	vertical bar
}	right brace	~	tilde

There must also be some way of dividing the source program into lines, typically a newline character or a sequence of newline and carriage return characters. Line endings are significant in one type of comments (see below).

The blank (space) character, tabulators, line endings, and comments (see below) are collective known as *whitespace*. Beyond separating tokens (see below), whitespace is ignored.

5.2 Comments

There are two kinds of comments:

- A comment introduced by // extends to the end of the line.
- A comment introduced by /* extends to the first matching occurrence of */.

Occurrence of // or /* inside a string literal (see below) does not introduce a comment.

Comments can be nested. All of the following are allowed:

```
/* nested block /* comment */ */
// /* block comment inside line comment */
/* // line comment inside block comment */
// // line comment inside line comment
```

5.3   Tokens

The characters making up an MDL program are collected into lexical tokens according to the rules presented in the following sections. There are six classes of tokens: operators, separators, identifiers, typenames, reserved words, and literals.

The compiler always uses the longest possible sequence of characters when reading from left to right to form a token, even if that does not result in a legal MDL program. For example, the sequence of characters "a--b" is interpreted as the tokens "a", "--", and "b", which is not a legal MDL expression, even though the sequence of tokens "a", "-", "-", "b" might constitute a legal expression.

5.4   Operators and separators

These are the operators of MDL grouped by precedence, from highest to lowest:

Operation Name	Operator Expression
scope resolution	*identifier* :: *identifier*
scope resolution	*identifier* :: *typename*
global scope resolution	:: *qualified_name*
global scope resolution	:: *qualified_type*
member selection	*expression* . *identifier*
subscripting	*expression* [*expression*]
function call	*qualified_name* (*expression*)
operator function call	`operator` *op* (*expression*)
value construction	*qualified_type* (*expression*)
type cast	`cast<`*qualified_type*`>` (*expression*)
postfix increment	*lvalue*++
postfix decrement	*lvalue*--
prefix increment	++*lvalue*
prefix decrement	--*lvalue*
logical not	!*expression*
unary minus	-*expression*
unary plus	+*expression*
bitwise complement	~*expression*
multiply	*expression* * *expression*
divide	*expression* / *expression*
modulo	*expression* % *expression*
add	*expression* + *expression*
subtract	*expression* - *expression*
left-shift	*expression* << *expression*
signed right-shift	*expression* >> *expression*
unsigned right-shift	*expression* >>> *expression*
less than	*expression* < *expression*
less than or equal	*expression* <= *expression*
greater than	*expression* > *expression*

greater than or equal	*expression* >= *expression*
equal	*expression* == *expression*
not equal	*expression* != *expression*
bitwise and	*expression* & *expression*
bitwise xor	*expression* ^ *expression*
bitwise or	*expression* | *expression*
logical and	*expression* && *expression*
logical or	*expression* || *expression*
conditional expression	*expression* ? *expression* : *expression*
simple assignment	*lvalue* = *expression*
multiply and assign	*lvalue* *= *expression*
divide and assign	*lvalue* /= *expression*
modulo and assign	*lvalue* %= *expression*
add and assign	*lvalue* += *expression*
subtract and assign	*lvalue* -= *expression*
left-shift and assign	*lvalue* <<= *expression*
signed right-shift and assign	*lvalue* >>= *expression*
unsigned right-shift and assign	*lvalue* >>>= *expression*
bitwise and and assign	*lvalue* &= *expression*
bitwise xor and assign	*lvalue* ^= *expression*
bitwise or and assign	*lvalue* |= *expression*
sequencing	*expression* , *expression*

Unary operators and assignment operators are right-associative; all others are left-associative.

See Section 6.6 for the definition of lvalues.

The separators of MDL are "{", "}", "(", ")", ":", ",", and ";". They group or delimit other syntactic elements of the language.

5.5   Identifiers and typenames

An *identifier* is an alphabetic character followed by a possibly empty sequence of alphabetic characters, decimal digits, and underscores, that is neither a typename nor a reserved word (see below). Declarations in the MDL syntax expect an identifier that may actually be a typename in case the declaration shadows this typename, such as a typename from a different scope.

A *typename* has the same lexical structure as an identifier, but is the name of a built-in type, a material name, a BSDF, EDF or VDF class name, or a type defined by the user with a structure, enumeration, or typedef declaration.

5.6   Unicode identifiers

Unicode identifiers are identifiers that can contain arbitrary unicode code points. Package and module names can be either identifiers or unicode identifiers. In no other contexts are unicode identifiers allowed.

A unicode identifier is a non-empty sequence of UTF-8 encoded characters [2] without single quotes or control sequences, enclosed in single quotes. The syntax of escape sequences is the same as for string literals as defined in Section 5.8.5.

5.7   Reserved words

These are the reserved words of MDL that can only be used in the way defined in this document:

```
annotation          double2     float       in                        operator
auto                double2x2   float2      int                       package
bool                double2x3   float2x2    int2                      return
bool2               double3     float2x3    int3                      string
bool3               double3x2   float3      int4                      struct
bool4               double3x3   float3x2    intensity_mode            switch
break               double3x4   float3x3    intensity_power           texture_2d
bsdf                double4     float3x4    intensity_radiant_exitance texture_3d
bsdf_measurement    double4x3   float4      let                       texture_cube
case                double4x4   float4x3    light_profile             texture_ptex
cast                double4x2   float4x4    material                  true
color               double2x4   float4x2    material_emission         typedef
const               edf         float2x4    material_geometry         uniform
continue            else        for         material_surface          using
default             enum        hair_bsdf   material_volume           varying
do                  export      if          mdl                       vdf
double              false       import      module                    while
```

These are additional words of MDL that are reserved for future use or to avoid misleading use. Using them results in an error.

```
catch          friend     half3x4    mutable          sampler       throw
char           goto       half4      namespace        shader        try
class          graph      half4x3    native           short         typeid
const_cast     half       half4x4    new              signed        typename
delete         half2      half4x2    out              sizeof        union
dynamic_cast   half2x2    half2x4    phenomenon       static        unsigned
explicit       half2x3    inline     private          static_cast   virtual
extern         half3      inout      protected        technique     void
external       half3x2    lambda     public           template      volatile
foreach        half3x3    long       reinterpret_cast this          wchar_t
```

5.8   Literals

literal_expression	:	*boolean_literal*
	|	*enum_literal*
	|	*integer_literal*
	|	*floating_literal*
	|	*string_literal* {*string_literal*}

boolean_literal	:	true | false

enum_literal	:	intensity_radiant_exitance | intensity_power

integer_literal	:	*INTEGER_LITERAL*

floating_literal	:	*FLOATING_LITERAL*

string_literal	:	*STRING_LITERAL*

Literals are a means to directly denote values of simple types.

5.8.1   Boolean literals

The Boolean literals are `true` and `false`.

5.8.2   Enumeration literals

Two enumeration literals, `intensity_radiant_exitance` and `intensity_power`, are reserved words. They are literals of the enumeration type `intensity_mode`.

5.8.3   Integer literals

Integer literals can be given in octal, decimal, or hexadecimal base.

A decimal literal is a non-empty sequence of decimal digits.

An octal literal is the digit zero followed by a non-empty sequence of octal digits (the digits from zero to seven inclusive).

A hexadecimal literal is the digit zero, followed by the character `x` or `X`, followed by a non-empty sequence of the *hexadecimal digits*, defined as the decimal digits and the letters `a`, `b`, `c`, `d`, `e`, `f`, `A`, `B`, `C`, `D`, `E`, and `F`.

5.8.4   Floating-point literals

A floating point literal is a possibly empty sequence of decimal digits, optionally followed by a decimal point (the character period) and a possibly empty sequence of decimal digits, optionally followed by an exponent given by the letter `e` or `E`, an optional sign (- or +) and a non-empty sequence of decimal digits, optionally followed by a type suffix. Either the decimal point or the exponent need to be present. There has to be at least one digit preceding or following the decimal point. The type suffix can be the letter `f`, `F`, `d`, or `D`.

A floating-point literal without type suffix or with type suffix `f` or `F` is of type `float`. A floating-point literal with type suffix `d` or `D` is of type `double`. Floating-point types are described in Section 6.9 on page 27.

A floating-point literal of type `float` is able to hold a value of type `double`, which is used in case the literal is converted to a double value.

5.8.5   String literals

A string literal is a possibly empty sequence of UTF-8 encoded characters [2] not including a double quote or control sequences, enclosed in double quotes. A string literal may not include a line ending. A string literal may be further restricted to 7-bit ASCII encoding or a fixed set of choices depending on context. String literals can be concatenated by juxtaposition.

Permitted escape sequences are a backslash followed by one of the following escape codes:

Escape Sequence	Description	Representation
\'	single quote	byte 0x27
\"	double quote	byte 0x22
\\	backslash	byte 0x5c
\a	alert (e.g., bell)	byte 0x07
\b	backspace	byte 0x08
\f	form feed	byte 0x0c
\n	new line	byte 0x0a
\r	carriage return	byte 0x0d
\t	horizontal tab	byte 0x09
\v	vertical tab	byte 0x0b
\\nnn	arbitrary octal value	byte nnn
\x$nn$	arbitrary hexadecimal value	byte nn
\u$nnnn$	arbitrary Unicode value	code point U+nnn
\U$nnnnnnnn$	arbitrary Unicode value	code point U+$nnnnnnnn$

6 Data types, values, and variables

type	:	[*frequency_qualifier*] (`auto` | *array_type*)
array_type	:	*simple_type* [[[*conditional_expression* | < *simple_name* >]]]
simple_type	:	[`::`] *relative_type*
relative_type	:	`bool` | `bool2` | `bool3` | `bool4`
		| `int` | `int2` | `int3` | `int4`
		| `float` | `float2` | `float3` | `float4`
		| `float2x2` | `float2x3` | `float2x4`
		| `float3x2` | `float3x3` | `float3x4`
		| `float4x2` | `float4x3` | `float4x4`
		| `double` | `double2` | `double3` | `double4`
		| `double2x2` | `double2x3` | `double2x4`
		| `double3x2` | `double3x3` | `double3x4`
		| `double4x2` | `double4x3` | `double4x4`
		| `color` | `string` | `bsdf` | `edf` | `vdf` | `hair_bsdf`
		| `light_profile` | `bsdf_measurement`
		| `material` | `material_emission` | `material_geometry`
		| `material_surface` | `material_volume` | `intensity_mode`
		| `texture_2d` | `texture_3d` | `texture_cube` | `texture_ptex`
		| *IDENT* [`::` *relative_type*]
frequency_qualifier	:	`varying` | `uniform`

MDL defines a collection of built-in data types tailored for the kind of tasks materials need to accomplish. In addition, these types can be used to define array types as described on page 43 and custom structures as described on page 47.

Below is a list of built-in MDL data types with a brief description of each type:

- `float`, `double` – A single real number.
- `int` – An integer, including positive and negative numbers as well as zero.
- `bool` – A Boolean value that is either `true` or `false`.
- `float2`, `float3`, `float4`, `double2`, `double3`, `double4` – Vectors with real number elements.
- `int2`, `int3`, `int4` – Integer vectors.
- `bool2`, `bool3`, `bool4` – Boolean vectors.
- `float2x2`, `float2x3`, `float3x2`, `float3x3`, `float4x3`, `float3x4`, `float2x4`, `float4x2`, `float4x4`, `double2x2`, `double2x3`, `double3x2`, `double3x3`, `double4x3`, `double3x4`, `double2x4`, `double4x2`, `double4x4` – Matrices of various dimensions.
- `texture_2d`, `texture_3d`, `texture_cube`, `texture_ptex` – Texture map samplers.
- `color` – An implementation independent representation of color.
- `string` – A character string.
- `light_profile` – A description of light emittance for real world lights; used for parameters of emission descriptions only.
- `bsdf_measurement` – A description of a measured bidirectional scattering distribution function (BSDF) that can be used with the corresponding elemental distribution function to render the measurement.

- `bsdf, edf, vdf, hair_bsdf` – Reference types for a BSDF, EDF, VDF, or hair BSDF respectively; used for parameters of materials only.

- `material, material_geometry, material_surface, material_emission, material_volume` – Struct-like types describing a material and its components.

- `intensity_mode` – An enumeration type used for one of the fields in the `material_emission` type to define the units used to control the emission intensity of lights.

Atomic types are keywords in MDL.

6.1   Constructors

A value of an MDL data type can be constructed by calling the type's constructor. The constructor syntax consists of the type name, followed by a comma separated list of arguments contained in parenthesis. For example, the following expression evaluates to a value of type `float3`:

```
float3(0.3, 0.1, 0.7)
```

Constructor calls are analogous to function calls. They allow, in addition to the above argument passing by position a style where arguments are passed by name. In this case, each argument consists of the parameter name separated from the initializing expression by a colon. The exact rules for argument passing are explained in Section 12.1. For example, the following expression evaluates to the same value of type `float3` as the previous example:

```
float3(x: 0.3, y: 0.1, z: 0.7)
```

Types can have several overloaded constructors. Two kinds of constructors exist for all types: the default constructor and the copy constructor. The default constructor takes no parameter. It is used to initialize values if no other initializer is provided. The copy constructor takes a parameter of identical type. It is used when a value is copied.

Constructors are defined specifically for each type in MDL; there are no user-defined constructors in MDL. The individual constructors are documented in the following sections for each corresponding type.

6.2   Variables

variable_declaration	:	*type variable_declarator*
		$\{$, *variable_declarator* $\}$;
variable_declarator	:	*simple_name* $[$ *argument_list* $\mid$ = *assignment_expression* $]$
		$[$ *annotation_block* $]$

A type followed by an identifier and semicolon declares a variable of that name and type in MDL. Multiple variables of the same type can be declared by separating them with commas.

Variables can be used in MDL for local variables in functions (Section 12) and as temporary read-only values in let-expressions (Section 13.8).

When declaring a variable the type's constructor can be invoked by appending the constructor parameters, enclosed in parenthesis, to the variable name in the declaration. If a variable declaration contains an initializer, it will be treated as if the variable was constructed taking the right-hand side of the assignment statement as the constructor's parameter.

For example, the following three cases are identical, which is to invoke the `float`-type constructor with the literal value `0.0` as a parameter and initialize the variable with the resulting value:

```
float x(0.0);
```

```
float y = float(0.0);
float z = 0.0;
```

Variables and parameters do not have to be initialized with an explicit constructor or initializer. In that case, the type's default constructor will be used to initialize the value. Note: In MDL, values are always initialized.

In the following sections, detailed descriptions of each type identify the overloaded constructor versions supported by that type.

6.3   Uniform and varying values and types

A value of an MDL data type can be *uniform* or *varying*. A common source for varying values are varying state functions, see Section 19, or varying function or material parameters, see Section 12.2 and 13.5.

Being uniform or varying is a type property and can be declared with the `uniform` and `varying` type modifiers, respectively. A variable of a uniform type can only be set to a uniform value. A variable of a varying type can be set to a varying value as well as to a uniform value. The resulting value in the variable is then always considered varying.

For example:

```
uniform float x = 0.0; // x is a uniform value
varying float y = x;   // y is a varying value
```

A type without a `uniform` or `varying` type modifier is *auto-typed*, that is, its uniform or varying property is determined by the actual use of the type. For variable declaration, the considered use of the variable includes all its occurrences; if any occurrence of the variable requires the variable to be varying then the type of the variable will be considered varying. This implies that possible uses of the variable where it would be required to be uniform are considered errors in the program.

For example:

```
float3 x = 0.0;        // auto-typed
uniform float3 y = x;  // ! error, because varying x cannot be assigned to uniform
x = state::normal();   // x becomes varying by assigning the varying state::normal
```

6.4   Placeholder type specifier

The type of a variable that is being declared can be automatically deduced from its initializer if it has any. In this case, the placeholder type specifier `auto` can be used for the variable in place of the explicit type.

For example:

```
auto f = 0.0;          // f has the type float
```

A placeholder type specifier can be further restricted with a `uniform` or `varying` type modifier.

If the placeholder type specifier is used to declare multiple variables, the deduced types must match.

For example:

```
auto i = 0, f = 0.0;   // ! error -- ill-formed with different initializer types
auto i = 0, j = i + 1; // well-formed with type deduced as int
```

Note: The placeholder type specifier becomes more useful with user-defined types (Section 8) and let-expressions in functions (Section 12.9) and materials (Section 13.8).

6.5   Operators

expression	:	*assignment_expression* { , *assignment_expression* }
assignment_expression	:	*logical_or_expression* 　　[? *expression* : *assignment_expression* 　　| *assignment_operator assignment_expression* 　　]
assignment_operator	:	= | *= | /= | %= | += | -= | <<= | >>= | >>>= | &= | ^= | |=
conditional_expression	:	*logical_or_expression* [? *expression* : *assignment_expression*]
logical_or_expression	:	*logical_and_expression* { || *logical_and_expression* }
logical_and_expression	:	*inclusive_or_expression* { && *inclusive_or_expression* }
inclusive_or_expression	:	*exclusive_or_expression* { | *exclusive_or_expression* }
exclusive_or_expression	:	*and_expression* { ^ *and_expression* }
and_expression	:	*equality_expression* { & *equality_expression* }
equality_expression	:	*relational_expression* {(== | !=) *relational_expression* }
relational_expression	:	*shift_expression* {(< | <= | >= | >) *shift_expression* }
shift_expression	:	*additive_expression* {(<< | >> | >>>) *additive_expression* }
additive_expression	:	*multiplicative_expression* {(+ | -) *multiplicative_expression* }
multiplicative_expression	:	*unary_expression* {(* | / | %) *unary_expression* }
unary_expression	:	*postfix_expression* |　(~ | ! | + | - | ++ | --) *unary_expression* |　*let_expression*
let_expression	:	`let` 　　(*variable_declaration* 　　| { *variable_declaration* {*variable_declaration*} } 　　) `in` *assignment_expression*
postfix_expression	:	*primary_expression* 　　{ ++ 　　| -- 　　| . *simple_name* 　　| *argument_list* 　　| [*expression*] 　　}

primary_expression	:	*literal_expression*
	|	*simple_type* [[ ]]
	|	(*expression*)
	|	cast < *array_type* > (*unary_expression*)
	|	operator *op argument_list*
operator_function_op	:	[] | ! | ~ | + | - | * | / | % | << | >> | >>> | < | <= | > | >= | == | !=
	|	& | ^ | | | && | || | ?
expression_statement	:	[*expression*] ;

Most MDL types support the arithmetic, assignment, and comparison operators listed in Section 5.4.

Operators are defined in global scope. Operators may have overloaded version for different built-in types of operands. Additional programmer-defined overloads are not allowed.

Some MDL types have member variables, which are accessed by placing a period character '.' after the type value followed by the name of the member. For example v.x accesses the x member of v.

The comma operator and ternary conditional operator (represented by the '?' character) are also supported for use in expressions. The comma operator evaluates to the value of the right-most expression in the comma-separated list of expressions and shares its type. The '?' operator evaluates to the value of the second or third operands depending on the result of the first operand, which must be of type bool. If the first operand is true the result is the second operand otherwise it is the third operand. The second and third operand must have the same type, which defines the type of the expression. Whether only the second or the third operand that is selected by the '?' operator is evaluated or whether both are evaluated is implementation dependent. Expressions in these operands should therefore be restricted to have no side effects.

The binary logical operators '&&' and '||' may or may not use short-circuit evaluation. The expressions for the second operand should therefore be restricted to have no side effects.

The return value of the type-cast operator expression cast<t>(v) is equal to v if the type t is equal to the type of the parameter value v with any uniform or varying type modifier removed.

Additionally, the type-cast operator is applicable where the type t differs from the type of the parameter value v in in certain cases of array types (Section 7.4), user defined structure types (Section 8.2), or enumeration types (Section 9.1). In all other cases, the use of the type-cast operator is an error.

The type of the result value is always equal to t with the uniform or varying modifier set to the modifier of the parameter value v, if it has any.

In the following sections, detailed descriptions of each type identify the operators supported by that type.

6.6   Lvalues and rvalues

The following values are *lvalues*:

- variables that are not read-only,

- function parameters in function bodies, but not in let-expressions (Section 12.9) nor function definitions using an expression (Section 12.6),

- the result of an array member access of an array-type lvalue,

- the result of a field access of a structure-type lvalue,

- the result of the pre-increment and pre-decrement operators,

- the result of the assignment operators, and

- the result of the type cast operator on an lvalue.

All other values are *rvalues*.

Lvalues are required as the argument to the increment and decrement operators, and as the left argument to the assignment operators.

6.7   Constant expressions

MDL makes use of *constant expressions* in some places. The type of a constant expression is one of:

- One of the following types:

bool	int	float	double	color	string
bool2	bool3	bool4	int2	int3	int4
float2	float3	float4	double2	double3	double4
float2x2	float2x3	float2x4	float3x2	float3x3	float3x4
float4x2	float4x3	float4x4	double2x2	double2x3	double2x4
double3x2	double3x3	double3x4	double4x2	double4x3	double4x4

- An array type with a base type that is a legal type for a constant expression.
- A user-defined struct type where all fields have a type that is a legal type for a constant expression.
- A user defined enumeration.

A constant expression may consist of:

- bool, int, float, double and string literals (see Section 5.8).
- Constructors for base types, vectors, matrices, colors, and strings.
- Constructors for user defined structs with constant expressions as arguments and where all parameters without arguments have constant expression default initializer.
- Enumeration values.
- Indexing with constant expressions into constant expressions of array type.
- Selection of struct fields from constant expressions of struct type.
- The built-in operators "&&", "||", "&", "|", "^", "<", "<=", "==", "!=", ">=", ">", "<<", ">>", ">>>", "+", "−", "*", "/", "%", "!", "~", ".", or "[]". A division by zero is an error.
- Call of a standard math function (see Section 20.2) where all arguments are constant expressions.

6.8   Global and local constants

constant_declaration	:	const *array_type constant_declarator* { , *constant_declarator* } ;
constant_declarator	:	*simple_name* (*argument_list* | = *conditional_expression*) [*annotation_block*]

Constants can be declared globally or locally using a variable declaration preceded by the const keyword. The uniform or varying type modifiers are not allowed on the variable type. The initialization is restricted to a constant expression. For example:

```
const float example_constant = 2 * 3.14159;
```

6.9   Scalars – float, double, int and bool

A `float` or `double` represents an approximation of a mathematical "real" number.

A `float` value is represented as a 32-bit value following the IEEE 754 single precision floating-point definition [3]. However, it is not required that the precision of internal processing match the IEEE 754 floating-point specification for floating-point operations. Similarly, treatment of conditions such as division-by-zero may lead to an unspecified result, but in no case should such a condition lead to the interruption or termination of processing.

A `double` value has at least as much precision as a `float` value. Similarly, treatment of conditions such as division-by-zero may lead to an unspecified result, but in no case should such a condition lead to the interruption or termination of processing

An `int` represents a signed integer number, which uses 32 bits, including a sign bit, in two's complement form. Operations resulting in overflow or underflow will wrap around to yield the low-order 32 bits of the result and not cause any exception.

A `bool` represents a single Boolean value with possible values `true` and `false`.

6.9.1   Constructors

A scalar can be zero initialized with the default constructor, or set to `false` in the case of the `bool` type. A scalar can be initialized from any other scalar value even if the result entails a loss of precision.

In the following, all constructors are explained in detail, while implicit conversions, which apply in addition, are documented in Section 6.9.2.

`float()`   The default constructor creates a zero-initialized scalar.
`double()`
`int()`

`bool()`   The default constructor creates a `bool` value initialized to `false`.

`float(float value)`
`float(double value)`
`double(double value)`

       A `float` or `double` can be constructed from any other scalar value, which may result in a loss of precision. When floating-point values are converted to floating-point types of less precision, the value is rounded to one of the two nearest values. It is implementation dependent to which of the two values it is rounded.

`int(int value)`
`int(float value)`
`int(double value)`

       An `int` can be constructed from any other scalar value, which may result in a loss of precision. When floating-point values are converted to `int`, the fractional part is discarded. The resulting value is undefined if the truncated value cannot be represented as `int`.

`bool(int value)`
`bool(float value)`
`bool(double value)`

       An `bool` can be constructed from any other scalar value. It is initialized to `false` for a numeric value equal to zero, and it is initialized to `true` for all non-zero numeric values.

```
bool(bool value)
```
        An `bool` can be constructed from another `bool` value.

For example:

```
float x(5);
int   y(x);
bool  z(x);
```

All three constructor calls above are legal and result in three variables initialized with the following values:

Variable	Value
x	5.0
y	5
z	true

6.9.2 Conversion

When required by use in an expression, an scalar value will be implicitly converted to another scalar type provided there is no loss of precision. For example, a `float` value can be automatically converted to the `double` type but an explicit constructor call or initialization is needed to convert a `double` value to the `float` type. Note: With the undefined precision of the scalar types, the conversion from an `int` value to the `float` or the `double` type may have in fact some loss of precision, but shall be allowed implicitly.

The following table lists the types each scalar type can be automatically converted to:

Type	Can be converted to
bool	int, float, or double
int	float, or double
float	double

Note: In addition to these implicit conversion, arithmetic and other operators provide overloads, for example, to support mixed scalar-vector operations. (See vector operations in Section 6.10.4 or mixed scalar-matrix operations in Section 6.11.4.)

6.9.3 Operators

The `float`, `double`, and `int` types support the following operators:

=	/	/=	+	+=	–
–=	*	*=	==	!=	<=
<	>=	>	++	––	

The `int` type additionally supports the modulo and bitwise operators:

%	%=	<<	>>	>>>	<<=	>>=	>>>=
~	&	^	|	&=	^=	|=	

The `bool` type supports the following operators:

=	==	!=	&&
!	||		

6.10   Vectors – float, double, int, and bool

MDL provides two, three, and four component vector types with either `float`, `double`, `int`, or `bool` component types. Vectors are named by taking the component type name and appending the dimension of the vector, which can be 2, 3, or 4.

For example:

```
float3 f3;  // a three-dimensional vector of floats
int2   i2;  // a two-dimensional vector of ints
bool4  b4;  // a four-dimensional vector of bools
```

6.10.1   Constructors

A vector can be zero initialized with the default constructor. A vector can be initialized from a single scalar, a series of scalars of the same number as the number of vector components, or a vector of the same dimension. In addition, a `float3` vector can be initialized from a value of type `color`.

In the following, all constructors are explained in detail with the vector type `float3` as a representative for all vector types, while implicit conversions, which apply in addition, are documented in Section 6.10.2.

`float3()`   The default constructor creates a zero-initialized vector.

`float3(float value)`

All components of the vector are initialized with the scalar `value`.

`float3(float x, float y, float z)`

The components of the vector are initialized with the values of x, y, and z. The fourth parameter in the case of a `float4` vector is named `w`.

`float3(float3 value)`
`float3(double3 value)`

A vector can be constructed from any other vector of equal dimension, which may result in a loss of precision.

`float3(color value)`

A vector of type `float3` can be constructed from a value of type `color`. The 'x', 'y', and 'z' components will be assigned the red, green, and blue color component values, respectively, in the linear sRGB color model. Note that this conversion may have significant runtime costs depending on the internal color representation of the `color` type. See Section 6.13 for more details on the `color` type.

Note: This constructor does not exist for the other vector types.

Some examples:

```
bool   b1 = true;         // a Boolean value to work with
int    i0 = 0,   i4 = 4;  // some scalar values to work with
float  s2 = 2.0, s3 = 3.0; // more scalar values
float4 v4(b1, s2, s3, i4); // 4-float constructor, implicit conversions to float
float3 v3(i0, b1, s2);    // 3-float constructor, implicit conversion of i0
bool3  vb3(v3);           // conversion of equal sized vectors with lost precision
```

These three vector constructor calls result in the three vectors initialized with the following values:

Variable	Value
v4	`<1.0, 2.0, 3.0, 4.0>`
v3	`<0.0, 1.0, 2.0>`
vb3	`<false, true, true>`

6.10.2 Conversion

When required by use in an expression, a value of a vector type will be implicitly converted to another vector type of the same length provided the element types allow implicit conversion.

The following table lists the automatic conversion rules for each vector type:

Type	Can be converted to
`bool` vectors	`int`, `float`, or `double` vectors
`int` vectors	`float` or `double` vectors
`float` vectors	`double` vectors

6.10.3 Members

The vector types support member variables to access their components and follow a common scheme to determine which members are available for each vector type.

The `'x'`, `'y'`, `'z'`, and `'w'` members provide access to up to four components. A particular vector type will only support the first `n` components where `n` is the dimension of the vector. For example, `float2` supports the `'x'` and `'y'` members.

Vector components can also be accessed using array indices and the array index can be a variable.

```
float4 v = ...;
float sum = 0.0;
for (int i=0; i<4; i++)
    sum += v[i];
```

In this example the vector `v` has its components summed using a loop.

6.10.4 Operators

Vectors support math operators in a component-wise fashion. The operator is applied to each component of the operand vectors independently and the result is a vector of the same size as the operands. Vectors support comparison operators returning a scalar `bool` value. The operand vectors must be the same size or one must be a scalar (in which case it is automatically promoted to a vector with the same dimension as the other operand).

The `float2`, `float3`, `float4`, `double2`, `double3`, `double4`, `int2`, `int3`, and `int4` types support the following operators:

=	/	/=	+	+=	-	-=
*	*=	==	!=	++	--	

The `int2`, `int3`, and `int4` types additionally support the modulo and bitwise operators, where the right-hand side of the shift operators must be a value of type `int`.

%	%=	<<	>>	>>>	<<=	>>=	>>>=
~	&	^	|	&=	^=	|=	

The `bool2`, `bool3`, and `bool4` types support the following operators:

```
=          ==        !=        &&        !          ||
```

The following example illustrates in its second line how implicit conversions of scalar values and above operator overloads work together. The `int` literal value 1 is implicitly converted to a `float` type to match the only applicable subtraction operator that takes a scalar on the left-hand side and a `float3` vector on the right-hand side.

```
float3 x(1, 2, 3);
float3 y = x - 1;
```

The resulting value of the y variable is `(0, 1, 2)`.

6.11   Matrices – float and double

MDL provides several matrix types with column and row sizes ranging from two to four. Matrix elements can be of type `float` or `double`. Matrix types are named `type[columns]x[rows]` where `type` is one of `float` or `double`, `[columns]` is the number of columns and `[rows]` is the number of rows.

Specifically, the built-in matrix types are: `float2x2`, `float2x3`, `float3x2`, `float3x3`, `float3x4`, `float4x2`, `float2x4`, `float4x3`, `float4x4`, `double2x2`, `double2x3`, `double3x2`, `double3x3`, `double3x4`, `double4x2`, `double2x4`, `double4x3`, and `double4x4`.

The matrix type `float4x4` is used to represent coordinate-system transformations in Section 19.2.

Note: The naming convention, the column-major order implied below, and the coordinate-system transformation conventions in Section 19.2 are compliant with the respective OpenGL conventions.

6.11.1   Constructors

A matrix can be default constructed or constructed from a single scalar, a series of scalars of the same number as the number of matrix elements, a series of vectors of the same number as the number of columns of the matrix, or a matrix of the same dimensions.

In the following, all constructors are explained in detail with the matrix type `float3x2` as a representative for all matrix types, while implicit conversions, which apply in addition, are documented in Section 6.11.2.

`float3x2()`

> The default constructor creates a zero-initialized matrix.

`float3x2(float value)`

> The diagonal elements of the matrix are initialized with the scalar `value` while the other elements are initialized with zero.
>
> For example, `float3x2(1.0)` results in the following matrix value:
>
> $$\begin{pmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \end{pmatrix}$$
>
> Or, `float4x4(1.0)` results in the 4×4 identity matrix.

`float3x2(float m00, float m01, float m10, float m11, float m20, float m21)`

> A matrix can be constructed from a series of scalars in column-major order where the number of scalars passed to the constructor is the same as the number of elements of the matrix.
>
> For example, `float4x3(1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.5, 0.0)` results in the following matrix value:
>
> $$\begin{pmatrix} 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.5 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{pmatrix}$$

```
float3x2(float2 col0, float2 col1, float2 col2)
```

> A matrix can be constructed from a series of vectors where each vector represents a column of the matrix. The dimension of the vectors must be the same as the size of columns in the matrix.
>
> In the following example, the matrix mat gets the same value as in the previous example of the element-wise constructor:
>
> ```
> float3 col0(1.0, 0.0, 0.0);
> float3 col1(0.0, 1.0, 0.0);
> float3 col2(0.0, 0.0, 1.0);
> float3 col3(0.0, 0.5, 0.0);
> float4x3 mat(col0, col1, col2, col3);
> ```

```
float3x2(float3x2 value)
float3x2(double3x2 value)
```

> A matrix can be constructed from any other matrix of equal dimensions, which may result in a loss of precision.

6.11.2 Conversion

When required by use in an expression, a value of the matrix type will be implicitly converted to another matrix type of the same dimensions, provided that the element types allow implicit conversion. For example, the legality of the implicit conversion from a value of type float to one of type double allows float matrices to be converted into double matrices.

6.11.3 Members

The matrix types use array notation to provide access to their members, which are columns of the matrix. An index of zero refers to the first column of the matrix and indices of up to $n - 1$ (where n is the number of columns) provide access to the remaining columns.

The data type of matrix columns are vectors with dimension equal to the number of rows of the matrix. Since columns are vectors and vectors support array syntax to access vector elements, individual elements of a matrix can be accessed with syntax similar to a multidimensional array.

For example:

```
float4x3 mat(1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.5, 0.0);
float3 col;
float element;

// col will equal <0.0, 1.0, 0.0> after the assignment
col = mat[1];

// element will equal 0.5 after the assignment
element = mat[3][1];
```

6.11.4 Operators

The matrix types support the following operators based on linear algebra:

=	/	/=	+	+=	-
-=	*	*=	==	!=	

The multiplication operator multiplies two matrices, a matrix and a vector, or a matrix and a scalar in a linear algebra style multiplication. When multiplying two matrices, the number of columns of the matrix on the left must be equal to the number of rows of the matrix on the right. The result of multiplying a `TxN` matrix with a `MxT` matrix is a `MxN` matrix. A vector can be multiplied on the right or left side provided the number of elements is equal to the number of rows when the vector is on the left side of the matrix and the number of elements is equal to the number of columns when the vector is on the right. A matrix can be multiplied component-wise with scalar.

The division operator is supported to divide a matrix component-wise by a scalar.

The equality and inequality comparison operators, `==` and `!=`, return a scalar `bool`. They require that the operands are matrices of the same dimension or one operand is a scalar. The matrix elements are compared component-wise. A scalar operand is first converted to a matrix of the same type using the corresponding constructor.

The assignment, add and subtract operators are applied component-wise and require that the operands are matrices of the same dimension.

6.12   String

A `string` is a sequence of characters of arbitrary length. MDL uses strings primarily as parameters to
identify options or user defined categories. Because of the restricted need for strings in a material language,
and the fact that some platforms have limited or no support for strings, MDL defines a limited set of string
handling functionality.

String literals and the MDL character set are described in Section 5.

6.12.1   Constructors

`string()`   The default constructor creates the empty string `""`.

`string(string value)`

> A string can be constructed from another string.

6.12.2   Operators

The `string` type supports the following operators:

$$= \qquad == \qquad !=$$

6.13   Color

The MDL `color` type represents values across a continuous spectrum of wavelengths. The type is an abstraction of the conventional RGB representation of colors that enables materials to work with renderers that use a more accurate representation and rendering of colors.

A value of the `color` type maps wavelengths to `float` values. Wavelengths are given as `float` values in nanometers [nm] that are in the range [`limits::WAVELENGTH_MIN`, `limits::WAVELENGTH_MAX`], where the range bounds are constants in the `stdlimits` module (see Section 17) that depend on, and are provided by, the renderer implementation.

The exact implementation of the `color` type is not subject of the MDL specification. An implementation does not have to represent a spectrum exactly, it may choose to approximate spectra. For example, a simple implementation may actually represent colors as conventional RGB triples.

Unless otherwise specified, operations will be performed using the vacuum wavelength $\lambda_0 = \lambda \cdot \eta$, where λ is the local wavelength in a medium with an index of refraction of η.

6.13.1   Constructors

`color()`   The default constructor creates a black color with zero amplitude everywhere.

`color(float value)`

The amplitude of the color value is everywhere initialized to the scalar `value`, creating a gray color of corresponding magnitude.

`color(color value)`

The copy constructor creates a copy of the color `value`.

`color(float r, float g, float b)`
`color(float3 rgb)`

A color can be constructed from three `float` values or a single `float3` value, where the 'x', 'y', and 'z' components are interpreted as red, green, and blue color component values, respectively, in the linear sRGB color model.

Converting a `float3` value to a `color` value and back to a `float3` value shall result in the same value up to some numerical precision inaccuracies.

`color(float[<N>] wavelengths, float[N] amplitudes)`

A color can be constructed from two `float` arrays that define samples for a smooth spectrum representation, for example, of unitless reflectivities. The first array contains the wavelengths in increasing order and the second array, which must be of equal size, contains the amplitude values at these wavelengths. The construction may choose an approximation to represent the spectrum.

The following example creates a color from a function `intensity(float lambda)`, which returns the value at wavelength `lambda`. It samples the function at the wavelengths recommended for color construction by the state function `wavelength_base()` and passes both arrays to the color constructor.

```
color create_color() {
    float[state::WAVELENGTH_BASE_MAX] wavelengths = state::wavelength_base();
    float[state::WAVELENGTH_BASE_MAX] values;
    for ( int i = 0; i < state::WAVELENGTH_BASE_MAX; ++i) {
```

```
        values[i] = intensity( wavelengths[i]);
    }
    return color( wavelengths, values);
}
```

Note: The construction of `color` values and the conversion between RGB values and color values potentially come at significant runtime costs depending on the implementation-defined color representation of the `color` type.

Note: The construction of `color` values from spectral data can differ depending on the kind of of data, for example, unitless reflectivities, for which the color constructor is suitable, or light emission intensities, for which the standard math function `emission_color()` is suitable.

6.13.2 Conversion

There are no implicit conversions from and to values of type `color`.

6.13.3 Operators

The `color` type supports the following math operators which work on the color values:

=	/	/=	+	+=	−
−=	*	*=	==	!=	

All operators are defined for the `color` type as parameter on both sides. The +, −, and * operators are additionally defined for all combinations of a `color` type added, subtracted, and multiplied with a `float`. The / operator is additionally defined for the division of a `color` type divided by a `float`.

The equality and inequality comparison operators, == and !=, return a `bool` type. All other operators return a `color` type.

6.14 Textures

The MDL texture types represent references to texture data, associated sampler settings and lookup functions in the standard library. There are four texture types for four different texture shapes:

- `texture_2d` references texel data stored in a two-dimensional uniform grid.
- `texture_3d` references texel data stored in a three-dimensional uniform grid.
- `texture_cube` references texel data stored in a collection of six two-dimensional uniform grids, one for each direction ($+x$, $-x$, $+y$, $-y$, $+z$, and $-z$).
- `texture_ptex` references texel data stored in the PTEX format for two-dimensional surfaces.

Conceptually, texel data is either represented consistently as a single floating-point value, a vector of floating-point values, or a color value over the whole texture.

The texture types must always be used with the uniform type modifier.

A parameter of texture type can have an invalid reference value if no texture data was provided.

The `texture_2d` type can reference a single texture image or a *uv-tileset*, which is a whole set of texture images that are placed at integer *uv*-positions in texture space. Except where noted otherwise, single texture images and uv-tilesets behave the same, where the single texture image is interpreted as a uv-tileset with a single tile at index position $(0, 0)$. One difference is the placement in *uv*-texture space: The *uv*-position of a single texture image can be controlled through the wrap mode and crop parameters of the texture lookup functions, while those parameters are ignored for a uv-tileset (Section 20.3).

For texture data with an inherent frame of reference in space, MDL makes the following recommendations on texture space placement and orientation:

- The origin of a `texture_2d` type is in the lower left corner of the texture data. The x-axis extends to the right and the y-axis extends to the top.
- The origin of a `texture_3d` type is in the lower left back corner of the texture data. The x-axis extends to the right, the y-axis extends to the top, and the z-axis extends to the front. This convention implies that the respective unit basis vectors, e_x, e_y, and e_z, form a right-handed coordinate system with $e_x \times e_y = e_z$.

6.14.1 Constructors

```
texture_2d()
texture_3d()
texture_cube()
texture_ptex()
```

        The default constructor creates an invalid reference value.

```
texture_2d( uniform texture_2d value)
texture_3d( uniform texture_3d value)
texture_cube( uniform texture_cube value)
texture_ptex( uniform texture_ptex value)
```

        A texture can be created from another texture value of equal texture type.

```
texture_2d(    uniform string name,
               uniform tex::gamma_mode gamma = tex::gamma_default,
               uniform string selector = "" )
texture_3d(    uniform string name,
               uniform tex::gamma_mode gamma = tex::gamma_default,
               uniform string selector = "")
texture_cube( uniform string name, uniform tex::gamma_mode gamma = tex::gamma_default)
texture_ptex( uniform string name, uniform tex::gamma_mode gamma = tex::gamma_default)
```

A texture can be created from a file path including an optional marker to select whole uv-tilesets, defined in Section 2.2, given as literal argument to the `name` parameter of type `string`. The file path needs to name a file or uv-tileset in one of the eligible texture file formats defined in Section 2.3. It is an error if the texture file or the uv-tileset does not exist.

A literal string value can be used as argument for the `selector` parameter to select a data set or channel in the texture file. The exact string values supported depend on the file format and are documented in Section 2.3. It is an error if the selector string does not name a data set or a channel in the texture file.

The `anno::usage` standard annotation can be used on texture parameters to pre-select selector values in an integration.

Note: The gamma mode determines if the integration needs to apply an inverse-gamma correction or not before using the texture. This enumeration type is defined as part of the standard module `tex` in Section 20.3.

6.14.2   Operators

The texture types support the following operators:

$$=\qquad\qquad ==\qquad\qquad !=$$

6.15   Light_profile

The MDL `light_profile` type is used to represent a reference to light profile data, which is typically provided by vendors of real-world physical lights to describe precisely how much light is emitted from a point light source in a particular direction.

The `light_profile` type must always be used with the uniform type modifier.

A parameter of type `light_profile` can have an invalid reference value if no light profile data was provided.

6.15.1   Constructors

`light_profile()`

> The default constructor creates an invalid reference value.

`light_profile( uniform light_profile value)`

> A light profile can be created from another light profile value.

`light_profile( uniform string name)`

> A light profile can be created from a file path, defined in Section 2.2, given as literal argument to the `name` parameter of type `string`. The file path needs to name a file in one of the eligible light profile file formats defined in Section 2.4. It is an error if the light-profile file does not exist.

6.15.2   Operators

The `light_profile` type supports the following operators:

<div align="center">

=   ==   !=

</div>

6.16   Bsdf_measurement

The MDL `bsdf_measurement` type is used to represent a measured bidirectional scattering distribution function (BSDF) that can be used with the corresponding elemental distribution function `df::measured_bsdf` in Section 21.1.4 to render the measurement.

The `bsdf_measurement` type must always be used with the uniform type modifier.

A parameter of type `bsdf_measurement` can have an invalid reference value if no measurement data was provided.

6.16.1   Constructors

`bsdf_measurement()`

> The default constructor creates an invalid reference value, which renders a black opaque material if used.

`bsdf_measurement( uniform bsdf_measurement value)`

> A BSDF measurement can be created from another BSDF measurement value.

`bsdf_measurement( uniform string name)`

> A BSDF measurement can be created from a file path, defined in Section 2.2, given as literal argument to the `name` parameter of type `string`. The file path needs to name a file in one of the eligible BSDF measurement file formats defined in Section 2.5. It is an error if the file does not exist.

6.16.2   Operators

The `bsdf_measurement` type supports the following operators:

$$= \qquad == \qquad !=$$

7 Arrays

$$array\_type \quad : \quad simple\_type \; [\, [\, [conditional\_expression \,|\, < simple\_name >] \,] \,]$$

Array types in MDL are similar in form to the typical array types of other programming languages, defining a sequence of data values of the same *element type*. Arrays are one-dimensional and of non-negative size, that is, arrays of zero size are allowed. Multi-dimensional arrays are not available in MDL.

MDL provides two kinds of array types: the *size-immediate array types* and the *size-deferred array types*. Both array types behave the same unless noted otherwise.

The size-immediate array type is the conventional array type whose size is immediately specified as a constant expression (see Section 6.7 for constant expressions). A size-immediate array type consists of a constant non-negative integer expression for the size within square brackets ([]) that follows the type identifier for the elements of the array. Two size-immediate arrays have the same type only if both the type of array element and their sizes are the same.

The following example shows a few variables of size-immediate array type:

```
int[4] channels;
float[3] weights;
bool[7] layer_active;
```

The size of a size-deferred array type is represented by a symbolic *size identifier*. The actual size is not defined immediately with the array type but deferred to the point where the array value is initialized, which can—for function and material parameters—be even outside of the MDL source files. Two size-deferred arrays have the same type only if both the type of array element and their size identifier are the same.

The size identifier, when used the first time, must be enclosed in angle-brackets (< >). This is the point of declaration of the size identifier. It is only allowed in function or material parameter lists, for example:

```
float sum_array( float[<count>] values);
```

The size identifier obeys normal scoping rules. It can also be used more than once to define further size-deferred arrays. All uses of a declared size identifier are then without the angle-brackets, which are reserved for declaring new size identifiers. The following example requires that both arguments need to be of the same type, and here in particular of the same array size, when calling this function:

```
float inner_product( float[<n>] a, float[n] b);
```

The value of the size identifier is a non-negative integer value of type int. It is not a l-value. However, although it cannot change its value, it is not a constant value in the sense of constant expressions of Section 6.7.

The full details about the use of size-deferred array types in function and material parameters are explained in Section 12.5.

7.1 Constructors of size-immediate arrays

Array constructors support only positional arguments and not named arguments, which are explained in Section 12.

---

type[*n*]()

>   The default constructor creates a size-immediate array value of the given element type *type* and given size *n*, where all elements are default constructed.

---

type[*n*](*type*[*n*] value)

> The copy constructor creates a size-immediate array value of the given element type *type* and given size *n*, where all elements are copy-constructed from the corresponding elements in `value`.

---

type[*n*](*type* value0, ..., *type* value$_{n-1}$)
type[](*type* value0, ..., *type* value$_{n-1}$)

> A constructor creating a size-immediate array value of the given element type *type* and of size *n*, where the elements are initialized with the parameter values. In the second variant of this constructor the array size is deduced from the number of arguments provided to the constructor.

Examples of size-immediate array constructors:

```
int[4] channels( 0, 1, 2, 3 );
int[4] channels2 = int[]( 0, 1, 2, 3); // identical to channels

float[3] weights  = float[3](); // zero initialized
float[3] weights2;              // identical to weights
```

7.2   Constructors of size-deferred arrays

Array constructors support only positional arguments and not named arguments, which are explained in Section 12.

---

type[*identifier*]()

> The default constructor creates a size-deferred array value of the given element type *type* and given symbolic size *identifier*, where all elements are default constructed.

---

type[*identifier*](*type*[*identifier*] value)

> The copy constructor creates a size-deferred array value of the given element type *type* and given symbolic size *identifier*.

Examples of size-deferred array constructors:

```
float array_examples( float[<count>] values) {
    float sum = sum_array( float[count]());   // default c'tor with all zeros
    return sum_array( float[count]( values)); // explicit copy c'tor
}
```

7.3   Conversion

For the purpose of function calls and overload resolution, see Section 12.4, a size-immediate array type can be implicitly converted to a size-deferred type of the same element type and compatible size identifier, and a dependent size-deferred array type can be implicitly converted to a defining size-deferred array type of the same element type. See Section 12.5 for all details on the use of size-deferred array types as function parameters.

7.4   Operators

A value of an array type can be assigned to a l-value of the same type with the assignment operator (=).

Array elements are accessed by a non-negative integer expression of type int in square brackets following the array expression. These *array indices* are zero-origin; the index of the first element is zero, the index of the nth element is $n - 1$.

```
float[3] weights;
bool[7] layer_active;
// ...
float red_factor = weights[0];
layer_active[6] = false;
```

Out-of-bounds accesses must be detected and a default-constructed value must be returned in this case.

The type-cast operator can be used to change the type of an array to another, *cast-compatible* array type. Two array types are cast-compatible if they are both of size-immediate or size-deferred type, they have the same number of elements, and the element type of one can be cast to the element type of the other array type.

8 Structures

struct_type_declaration	:	struct *simple_name* [*annotation_block*]
		{ {*struct_field_declarator*} } ;
struct_field_declarator	:	*type simple_name* [= *expression*]
		[*annotation_block*] ;

MDL supports the definition of user-defined structures. A structure is a collection of named variables, possibly of different types. The declaration of a structure defines a new type name.

A structure is declared using the keyword `struct` followed by the name of the structure and the declaration of member variables, the structure's *fields*, enclosed in curly braces. Fields are declared with the same syntax as local variable declarations and may have an initializer expression. A field name can be any legal MDL identifier, though it cannot have the same name as the structure type.

Fields can have any built-in type or another user-defined structure type to produce a nested structure. A field can also have a size-immediate array type. Size-deferred array types are not allowed as field types.

Fields can have the uniform or varying modifier on their field types. In addition, the structure type can, when used, have another uniform or varying modifier for the whole structure type, which applies then to all field types. In this case, it is allowed if a field has already the same modifier on its type, but it is an error if it has a different modifier on its type.

For example, the following structure definition defines the type `color_pair`:

```
struct color_pair {
    color dark;
    color bright;
};
```

Once defined, a structure type can be used in the same manner as MDL's built-in types; to declare variables, function parameters and material parameters.

```
color_pair checkerboard;
```

A field may define an initialization value in the structure definition. The value can be any expression of that field's type including references to previous fields and function calls. The value is preceded by an equals sign (=).

```
struct color_pair {
    color dark   = color(0.2, 0.2, 0.2);
    color bright = color(1.0, 0.2, 0.1);
};
```

A structure can contain both uninitialized and initialized fields. All uninitialized fields, if any, must precede the first initialized field. (This restriction follows the requirements for default parameter values in function definitions; see Section 12.)

8.1 Constructors

A structure declaration looks generically like

```
struct structure_type {
    T₁    name₁ ;
    ...
    Tᵢ₋₁  nameᵢ₋₁ ;
    Tᵢ    nameᵢ = initializerᵢ ;
    ...
    Tₙ    nameₙ = initializerₙ ;
};
```

where fields with initializer follow fields without initializer, and either or both can be omitted. With this notation, the following constructors are defined for each structure type:

---

structure_type()

> The default constructor initializes all fields without initializer with their respective default constructor and all fields with initializer with the respective initializer value.

---

structure_type(*structure_type* `value`)

> The copy constructor creates a field-wise copy of `value`.

---

structure_type(T_1 *name*$_1$, ..., T_{i-1} *name*$_{i-1}$, T_i *name*$_i$ = *initializer*$_i$, ..., T_n *name*$_n$ = *initializer*$_n$)

> A constructor with a parameter for each field, which allows to define a value for each field at definition. Passing arguments to constructors is identical to passing arguments to functions described in Section 12. In particular, all fields without initializer require an explicit argument while all fields with initializer can be optionally left out, which initializes them to the value of their initializer expression. Note that, in addition, the default constructors mentioned above create a value of a structure type without providing any argument to any field.

For example, given the following definition of `polygon`

```
struct polygon {
    int sides;
    color fill_color = color(1,1,1);
    color edge_color = color(0,0,0);
};
```

a variable of type `polygon` can be created with its constructor:

```
polygon triangle( 3, color(1, 0, 0), color(0.5, 0.5, 0.5));
```

Another variable of type `polygon` can be created with its default constructor:

```
polygon nogon;
```

The value of `nogon` is equal to `polygon(0)`, and also `polygon(0, color(1,1,1), color(0,0,0))`, which makes all default constructed values and initializers explicit.

8.2 Operators

A value of a structure type can be assigned to a l-value of the same type with the assignment operator (=).

Fields are referenced with the usual dot notation of the member selection operator, with a structure variable name followed by a dot (.) and the field name:

```
checkerboard.dark   = color(0.2, 0.2, 0.2);
checkerboard.bright = color(1.0, 0.2, 0.1);
// ...
color tile_color = checkerboard.dark;
```

The type-cast operator can be used to change the type of a structure to another, *cast-compatible* structure type. Two structure types are cast-compatible if they have the same number of fields and if each pair of fields of equal position in the respective structure type can be cast from one to the other. The names of the fields do not matter, only the order in the structure definition.

For example, given the following alternative definition of a structure with two color fields:

```
struct two_colors {
    color c1;
    color c2;
};
```

We can assign a value of the `color_pair` structure from above to a variable of this new structure using a type-cast operator expression:

```
color_pair col1( color(0.1), color(0.2));
two_colors col2 = cast<two_colors>(col1);
```

9 Enumerations

enum_type_declaration	:	enum *simple_name* [*annotation_block*] {
		enum_value_declarator { , *enum_value_declarator* } [,]
		} ;

| *enum_value_declarator* | : | *simple_name* [= *assignment_expression*] [*annotation_block*] |

MDL provides the capability to define an enumeration as a convenient way to represent a set of named integer constants.

An enumeration is declared using the keyword `enum` followed by a comma separated list of identifiers, the *enumerators*, enclosed in curly braces. The list of enumerators can end with a trailing comma. An enumerator cannot have the same name as the enumeration type.

For example:

```
enum detail { low, medium, high };
```

The enumerators can be explicitly assigned literal values as well.

For example:

```
enum detail {
    low    = 1,
    medium = 2,
    high   = 3
};
```

This example defines a new type called `detail` with possible values of `low`, `medium` and `high`.

Enumeration type values can be implicitly converted to integers which results in an integer with the explicitly assigned value. If explicit values are not specified, each element is assigned the value of its predecessor plus one. The first element is assigned the value zero.

The values associated with an `enum` are not required to be unique within the type. For example, the following are both legal `enum` declarations:

```
enum bool_states {
    on     = 1,
    yes    = 1,
    off    = 0,
    no     = 0
};

enum foo {
    a = 2,
    b = 1,
    c        // c will implicitly be assigned the value 2
};
```

The declaration of an enum defines a new type name and anonymous enums are not supported. The enum elements themselves define a symbol within the scope where the enum is declared.

The enum default constructor has the value of the first enumeration value.

9.1 Operators

The type-cast operator can be used to change the type of an enumeration to another, *cast-compatible* enumeration. Two enumerations are cast-compatible if they have the same set of enumerator integer constants. The names of the enumerators or if multiple enumerators share the same constants do not matter.

For example, given the following definition of a two-valued enumeration:

```
enum flag {
    false_state,
    true_state
};
```

We can assign a value of the `bool_states` enumeration from above to a variable of this new enumeration using a type-cast operator expression:

```
bool_states b( yes);
flag f = cast<flag>(b);  // f has the value true_state
```

10   Typedef

alias_type_declaration   :   `typedef` *type simple_name* `;`

The `typedef` specifier allows a new type name to be introduced which acts as a synonym for an existing type name. To declare a new type name, the `typedef` specifier is followed by the name of an existing type, an optional array specifier, and after that the new name, which thereafter acts as a synonym for the existing type.

For example:

```
typedef int number;
```

This defines a new type name `number` which is syntactically synonymous with `int`.

Declarations that use `typedef` to define a type name can appear at the file scope level and local scope levels in functions. On file scope level the new type name is valid from the location at which it is declared to the end of the file. On local scope levels the new type name is valid from the location at which it is declared to the end of the local scope.

Once a type name is defined it cannot be redefined in the same scope to name a different type.

The size in a type name for a size-deferred array is bound at the first use of this type in a scope.

Note that `typedef` does not introduce a new type, but instead only an additional name for an existing type. This means that for the purpose of differentiating parameters to match overloaded functions, the type name is not enough for two parameters to be considered different.

For example the following is not legal:

```
typedef int number;

int overload_example( number x) {}
int overload_example( int    x) {} // error -- redefinition of my_function
```

11 Control flow

compound_statement	:	{ {*statement*} }

statement	:	*compound_statement*
	|	*type_declaration*
	|	*constant_declaration*
	|	*variable_declaration*
	|	*expression_statement*
	|	*if_statement*
	|	*switch_statement*
	|	*while_statement*
	|	*do_statement*
	|	*for_statement*
	|	*break_statement*
	|	*continue_statement*
	|	*return_statement*

type_declaration	:	*alias_type_declaration*
	|	*struct_type_declaration*
	|	*enum_type_declaration*

MDL supports the familiar programming constructs that control the flow of a function's execution. Specifically these are:

- The loop statements `for`, `while`, and `do-while`. The keywords `continue` and `break` are supported to control execution of the loop.
- The branch statements `if` with optional `else` clauses and `switch` statements with cases and optional defaults.
- A `return` statement to terminate a function and return a value.

11.1 Loops

for_statement	:	`for` ((*variable_declaration* | *expression_statement*)
		[*expression*] ; [*expression*])
		statement

while_statement	:	`while` (*expression*) *statement*

do_statement	:	`do` *statement* `while` (*expression*) ;

A for loop is declared using the keyword `for` followed by three expressions separated by semicolons and enclosed in parenthesis. The first expression is evaluated once before the loop begins. The second expression is evaluated once at the beginning of each iteration of the loop and will terminate the loop if it evaluates to `false`. The third expression is evaluated once at the end of each iteration of the loop. The loop body follows the `for` statement.

For example:

```
for (int i=0; i<10; i++) {
    // ...
}
```

Note that the first expression can declare variables which are visible in scope within the second and third expressions as well as the loop body.

The `continue` statement can be used in the body of the `for` loop to jump to the end of the current loop iteration.

The `break` statement will terminate the loop without further evaluation of the expressions in the `for` statement.

The `do` and `while` loop constructs are similar to each other. A `while` loop begins with the keyword `while` followed by an expression enclosed in parenthesis followed by the loop body. The body of the `while` loop will be executed as long as that expression evaluates to `true`.

When used in `do` or `while` loops, the `continue` statement will jump control to the end of the loop. The `break` statement will terminate the loop.

A `do` loop begins with the keyword `do` followed by the loop body and a while statement. The body will execute until a `break` statement is encountered or the expression in the `while` statement evaluates to `false`. The `while` test will be performed at the end of each iteration through the loop instead of at the beginning.

For example:

```
 while (x<n) {          // a while loop
    if (x==0) break;
    // ...
 }

 do {                   // a do loop
     // ...
 } while (x<n);
```

11.2 Branches

if_statement	:	if (*expression*) *statement* [else *statement*]
switch_statement	:	switch (*expression*) { {*switch_case*} }
switch_case	:	case *expression* : {*statement*} | default : {*statement*}

An `if` statement is declared using the keyword `if` followed by an expression contained in parenthesis followed by a statement that will be executed if the expression evaluates to `true`.

The `else` keyword can optionally follow indicating a statement that will be executed if the expression evaluates to `false`. In nested conditional statements, an else statement matches the closest unmatched if statement.

For example:

```
if (x<n) {
    // statements that execute if x<n
} else {
    // statements that execute if not x<n
}
```

Switch statements allow control to jump to a selected body of statements based on an integral value. A switch statement is declared using the keyword `switch` followed by an expression enclosed by parenthesis. The expression must evaluate to an `int` valued expression. Following this is a series of `case` blocks enclosed

in curly braces.

The case blocks are declared using the keyword `case` followed by a colon, then a constant integral value, and finally the statements of the case block. If the value of the expression in the `switch` statement equals the case value, that case block will be executed. Execution will fall through to the subsequent case block unless control is terminated with a `break` statement.

An optional default case block can be declared using the `default` keyword followed by a colon and then the statements to be executed if no other case statement matches the expression value.

A case block has its own scope that extends to the next case block or the end of the switch block if it is the last case block. In consequence, variables declared in a case block are not accessible in any other case block.

For example:

```
switch (x) {
    case 0:
        // statements that will be executed if x==0
        break;
    case 1:
        // statements that will be executed if x==1
        break;
    case 2:
        // statements that will be executed if x==2
        break;
    default:
        // statements that will be executed if x!= 0, 1, or 2
        break;
}
```

11.3   Jumps

break_statement	:	`break ;`
continue_statement	:	`continue ;`
return_statement	:	`return` *expression* `;`

The return statement terminates execution of the current function and returns control to the calling function or completes execution of the function if the current function has been called by the renderer.

A return statement is declared using the `return` keyword followed by a return value, whose type is equal to or has an implicit conversion to the return type of the function.

The `break` statement is used to terminate a loop or `switch` statement. The `continue` statement is used to terminate an iteration of a loop and proceed to the next iteration of the loop.

The `return, break,` and `continue` statements all cause the flow of control to jump to a new location in the code.

12 Functions

function_declaration	:	*type* [*annotation_block*] *simple_name*
		$\quad$ *parameter_list* [*frequency_qualifier*] [*annotation_block*]
		$\quad\quad$ (; | *compound_statement*)
	|	...
parameter_list	:	([*parameter* { , *parameter* } [,]])
parameter	:	*type simple_name* [= *assignment_expression*]
		$\quad$ [*annotation_block*]
postfix_expression	:	*primary_expression*
		$\quad$ { *argument_list*
		$\quad$ | ...
		$\quad$ }
argument_list	:	(
		$\quad$ [*named_argument* { , *named_argument* }
		$\quad$ | *positional_argument* { , *positional_argument* }
		$\quad\quad$ { , *named_argument* }
		$\quad$]
		)
named_argument	:	*simple_name* : *assignment_expression*
positional_argument	:	*assignment_expression*

MDL can define global, pure functions outside of material declarations that can be called from other functions or to provide values to material input parameters. Function calls are not allowed to be recursive.

A function is declared and defined in the main scope of a source file. The declaration consists of the return type, followed by the function name, followed by a list of function parameters surrounded by parenthesis. The parameter list is a comma-separated list of parameter declarations, each comprised of a type name followed by the parameter name and an optional default initializer. The parameter list can end with a trailing comma. Parameters with default initializer must follow parameters without initializer. Default initializer can refer to parameters before them. For example:

```
float function_example( float a, float b = 0.0, float c = b);
```

Functions must have a declaration that appears before any reference to the function is made. The function body can be included as part of the declaration or a separate function definition can occur later in the source file, after the function declaration. It is not an error to have the same function declaration more than once in an MDL file if only the first declaration uses default initializers. The function definition must be unique.

The function body opens a new scope for variable definitions. In addition, function parameters are part of the function body scope. It is thus not possible to shadow function parameters immediately in the function body.

Function parameters are lvalues and can be modified in the function body. This is not allowed if the function is implemented as an expression (see Section 12.6).

Unused function parameters may create a warning message at compilation time. Such a warning can be suppressed with the unused() annotation described in Section 14.

Global functions can be called from material parameter initializers or from other functions. A function call consists of the name of the function followed by a list of function arguments surrounded by parenthesis. The argument list is a comma-separated list of expressions. The argument list may be empty. The argument list can end with a trailing comma. A function call is an expression which has the type of the return type of the function declaration and is then subject to implicit conversion if the return value is used. For example, above declaration can be called as follows with its return value assigned to a variable:

```
double d = function_example( 5.0);
```

Function arguments are evaluated and assigned in the order from left to right to the corresponding parameters. Parameters without an argument must have a default initializer. Default initializers are also evaluated in the order from left to right.

For example, above function call is equivalent to:

```
double d = function_example( 5.0, 0.0, 0.0);
```

In addition to such *positional arguments*, where the position in the argument list decides to which parameter name an argument binds, MDL supports *named arguments*, where the parameter name is given explicitly with a *parameter selector* and separated with a colon from the argument value. This simplifies the use of functions if only a few of its parameters get values and the others remain default initialized.

For example, above function call is also equivalent to the following three variants:

```
double d1 = function_example( a: 5.0);
double d2 = function_example( b: 0.0, a: 5.0);
double d3 = function_example( c: 0.0, a: 5.0);
```

Note: Named arguments imply that the name of function parameters are part of the function signature. The name is not an implementation decision for a function and cannot be changed without considering all function calls.

Positional and named arguments can be used in a single function call. Positional arguments must be provided first and followed by named arguments.

All parameters without default initializer must have a value provided in the call, either through a positional or named parameter. Positional arguments can also be used on parameters with default initializers. No parameter is allowed to have more than one argument setting its value in a function call. This can occur with multiple named arguments, which is always a function call error. It can also occur with a combination of a positional and named argument, which eliminates this function declaration from the overload set (see overload resolution in Section 12.4) while other function declarations might still match.

12.1   Parameter passing

parameter	:	*type simple_name* $[=$ *assignment_expression* $]$
		$[$*annotation_block*$]$

Function arguments are semantically passed by value to function parameters. The argument's value is copied into the function being called, but the parameter's value is not copied back out. Results are only passed back to the callee through the functions return value. Multiple results need to be packaged into a suitable type, such as a structure type or array type.

A function call is *matching* a function declaration if it has the same function name and its arguments match the parameter types. An argument matches a parameter type if the type of the argument expression is equal to the parameter type or an implicit conversion exists from the type of the argument expression to the parameter type including an implicit promotion from a uniform type to a varying type.

The copying behavior described above specifies the semantics of function parameter passing. A particular MDL implementation may choose another implementation, for example, for better performance, as long as the described copy-semantic behavior is guaranteed.

A function return value must be initialized with a return statement.

12.2   Uniform and varying parameters and functions

Function parameter types can be explicitly declared uniform or varying. Otherwise they are auto-typed and have the same property as the call arguments.

Note: For larger parameter lists auto-typing may lead to many possible combinations of which some may not be legal for type reasons, such as a varying value that cannot be assigned to a uniform parameter or variable. These illegal combinations must be detected at compilation time with an error diagnostic, but, otherwise, these combinations may not necessarily require different implementations.

A function return type can be explicitly declared uniform or varying. Otherwise it is auto-typed. In case the return type is auto-typed, there can only be two sources that can make the return type varying, otherwise it will be uniform: varying function parameters and function calls in the function body that return varying values. To simplify the static analysis of functions, an auto-typed return type is defined to be varying if and only if one or both of the following two conditions apply:

1. At least one of the function parameters is varying. This is independent of whether the actual varying value would influence the return value or not.

2. The function body contains calls of other functions that are varying or have varying return types. This is independent of whether the actual execution of the function body would call these functions and whether the function results would influence the return value or not.

A compiler can analyze the second condition. However, MDL allows a programmer to declare explicitly if a function is varying or uniform — if the second condition is met or not — by placing the `varying` or `uniform` keyword after the closing parenthesis of the parameter list.

For example:

```
float3 uniform_function_example( float3 param) uniform;  // function declaration

float3 varying_function_example( float3 param) varying { // function definition
    return param + state::normal();
}
```

For a varying function, an auto-typed return type is always varying. More interesting is a uniform function: The compiler can guarantee that the implementation does not call varying functions and when calling it, an auto-typed return type is varying if and only if one of the function arguments is varying, and it is uniform otherwise.

This allows the natural and concise implementation of functions that can be used in a context of varying values as well as uniform values, such as standard library functions.

For example:

```
float sin( float a) uniform;
```

Calling this `sin` function with a varying argument results in a varying result value and calling it with an uniform argument results in an uniform result value.

12.3   Function and operator overloading

Multiple functions with the same name can be defined, called *function overloading*, provided they differ at least by the number or types of parameters. It is not sufficient for overloaded functions to only differ by return type, by name of parameters, or by their uniform, varying, or auto-typed property. For the purpose of being a different parameter type in this definition, it is also not sufficient if two types differ just by their uniform, varying, or auto-typed property.

A module (Section 15) always imports and exports all overloads of a function together. In addition, a module can add additional overloads to a function that it imports unqualified and may re-export this set of overloads again.

Note: The rules on imports prevent that function definitions from different modules are imported unqualified in the same module at the same time. The set of overloaded functions is thus always declared in a single module.

Various operators in MDL are overloaded for different parameter types, but additional user-defined overloads are not allowed.

12.4   Function overload resolution

Scope and overload resolution is the process that decides which function definition or operator is called at a particular function or operator call location. Everything said in this section for functions applies for operators as well unless specifically said otherwise. The handling of operators is simplified to the extent that all operators are defined in global scope and no additional user-defined overloads exist.

The identifier used in a function call is searched from the innermost scope enclosing the call outwards until a scope is found in which this identifier is declared. This declaration must declare a function, otherwise the program is ill-formed. The set of all function declarations in that scope with the same identifier is now considered for overload resolution.

Qualified identifiers are searched for in the module named in the qualification of the identifier. A similar set of all function declarations in that module scope is now considered for overload resolution.

All function declarations for which the signature does not match the call are eliminated from the set. A function signature S does not match the call if:

- The type of a positional argument in the call is not equal to the type of the parameter in that position in S or does not have an implicit conversion from the argument type to the parameter type.

- The parameter name of a named argument in the call does not exist in S.

- The type of a named argument in the call is not equal to the type of the named parameter in S or does not have an implicit conversion from the argument type to the parameter type.

- A parameter is specified more than once in the call if applied to S.

If the set of matching function declarations is empty after the above eliminations, the program is ill-formed.

If the set contains two or more function declarations, these will be compared pairwise and the *less specific* declaration will be removed from the set. This process is iterated until no further eliminations are possible.

If the set contains only one function declaration after the above eliminations, the corresponding function is called. Otherwise the overload resolution is ambiguous and the program is ill-formed.

A function signature T is less specific than a function signature U if for each positional or named argument that is used in the function call the types of the corresponding parameters are identical or there exists an implicit conversion from the type of the parameter of U to the type of the parameter of T.

Note: Above rules imply in MDL that if exactly one function declaration exists in the overload set for which all parameters match exactly without implicit conversions, the corresponding function is called.

The following example shows a few cases of which function declaration is chosen for which function call.
Note that the overload of the standard library function is not necessarily recommended in practice.

```
using ::std import max;            // (1) unqualified import of all overloads of max

int foo( float  x);                // (2)
int foo( double x);                // (3)

int bar( int    a, int    b);      // (4)
int bar( float  a, double b);      // (5)
int bar( double b, float  b);      // (6)

float max( int a, float b);        // (7) (not recommended to overload std library)

int overload_resolution_example() {
    foo( 1);                // calls (2) since (2) is more specific than (3)
    foo( 1.0f);             // calls (2) since (2) is an exact match
    foo( 1.0d);             // calls (3)

    bar( 1, 1);             // calls (4)
    bar( 1.0f, 1.0f);       // ! fails with (5) and (6) being the ambiguous matches

    max( 1, 1);             // calls max using (1), the max(int,int) from std::
    max( 1, 1.0f);          // calls (7) as an exact match
}
```

Note: Function overloads are more naturally used with positional than with named arguments. The
following example illustrates some of the possible results with named arguments.

```
int foo( int   a = 0, float b = 0);  // (1)
int foo( float b = 0, float a = 0);  // (2)

int overload_resolution_example() {
    foo();                  // ! fails with (1) and (2) being the ambiguous matches
    foo( 1);                // calls (1) since here (2) is less specific than (1)
    foo( 1.0f);             // calls (2)
    foo( a: 1);             // calls (1) since here (2) is less specific than (1)
    foo( 1, b: 1.0f);       // calls (1) because the call would set b twice for (2)
    foo( a: 1, b: 1.0f); // calls (1) since here (2) is less specific than (1)
}
```

12.5   Function parameters of size-deferred array type

A size-deferred array type, see Section 7, can be used for function parameters. When the function is called,
the size identifier — as a read-only variable of type `int` — is added to the scope of the function. The value of
this identifier is then initialized to the size of the array passed as the function argument. The size identifier
can be used throughout the function scope as a read-only value as any other variable of type `int`.

For example, the following function has one parameter, a size-deferred array named `values`.

```
float sum_array( float[<count>] values) {
    float result = 0.0;
    for (int i = 0; i < count; ++i)
        result += values[i];
    return result;
```

```
    }
```

The name of the size identifier of the `values` array is `count`. Within the body of the function, `count` can then be used to control the `for` loop.

Any size-immediate or size-deferred array value can be passed as a function argument of a size-deferred array parameter.

For example, in the following call of `sum_array`, the value of the `count` size identifier is 4. The initialized value of `total_weight` from the result of the function call is 2.4.

```
    float[4] weights( .2, .3, .5, 1.4 );
    float total_weight = sum_array(weights);
```

Size-deferred arrays using different identifiers inside the angle brackets are of different type. It is still possible to test the sizes at run-time and provide component-wise operations. For example:

```
    float inner_product( float[<n>] a, float[<m>] b) {
        if (n != m)
            return 0.0;
        float result = 0.0;
        for (int i = 0; i < n; ++i)
            result += a[i] * b[i];
        return result;
    }
```

In above example, the array sizes can be enforced to be equal by using the same size identifier for both arrays; enclosed in angle-brackets (`<>`) at the first occurrence and plain inside the square-brackets (`[]`) at all later occurrences. For example:

```
    float inner_product( float[<n>] a, float[n] b) {
        float result = 0.0;
        for (int i = 0; i < n; ++i)
            result += a[i] * b[i];
        return result;
    }
```

Assuming both versions of `inner_product` are offered as function overloads, which is possible, a function call would choose this overload of `inner_product` if both arguments are of the same type. If they are of different type, the first implementation is chosen, although the actual array sizes my be equal.

There could be further specializations of `inner_product`, for example:

```
    float inner_product( float[2] a, float[2] b) {
        return a[0]*b[0] + a[1]*b[1];
    }
```

This overload of `inner_product` would only be chosen if the argument arrays are of size-immediate array type `float[2]`. It would never be chosen if one or both arguments are of a size-deferred array type.

The return type of a function may be a size-deferred array type, but the identifier inside the square brackets must already have been declared as the array size of (at least) one of the functions parameters. For example:

```
    int[n] id( int[<n>] a) {
        return a;
    }
```

It is possible to declare local variables of size-deferred array type if the size identifier comes from a parameter declaration. For example:

```
int local_variable_example( int[<n>] a) {
    int[n] b = a; // copy constructed array of same value
    float[n] c;   // default constructed array of same size
    ...
}
```

Another example illustrates the use of a local variable of a dependent size and its use to accumulate a result returned through a size-deferred array return type:

```
float[n] scale( int[<n>] a, float s) {
    float[n] result;
    for (int i = 0; i < n; ++i)
        result[i] = s * a[i];
    return result;
}
```

Any array of a given element type can be passed as an argument for a parameter that is declared as a size-deferred array type of the same element type. For example:

```
float magic_sum( float[<n>] a) {
    float[3] b( 0, 1, 2);
    return sum_array(a) + sum_array(b);
}
```

Array parameters can have default initializers like other parameters:

```
float initializer_example( float[<n>] a = float[](1.0)) {
    return sum_array(a);
}
```

For size-deferred array parameters, a function call can nonetheless use an array argument of different size than used in the initializer.

```
float result = initializer_example( float[](3.0, 4.0, 5.0));
```

12.6   Function definition using an expression

function_declaration   :   ...
                              | *type* [*annotation_block*] *simple_name*
                                  parameter_list [*annotation_block*] = *expression* ;

Besides the conventional definition of functions with a procedural function body (Section 12), MDL allows the definition of a function using an expression. This kind of function definition is less expressive, but an important strict subset that is easier to work with, in particular, in the context of node graph editors.

Instead of the procedural function body, the function definition uses an expression for its definition. The expression can reference all function parameters as read-only rvalues.

The following example implements a function to square a floating point value:

```
float square( float value) = value * value;
```

Semantically, a function definition using an expression is equivalent to a function with a procedural body that contains only a return statement with the expression as return value.

The example is thus equivalent to:

```
float square( float value) {
```

```
        return value * value;
    }
```

12.7   Function variant

function_declaration   :   . . .
                                | *type* [*annotation_block*] *simple_name*
                                        (*) [*annotation_block*] = *expression* ;

A *function variant* is a short-hand notation to create a new function definition where only (some) default initializers of an already existing function have been changed, while all parameters remain exposed as parameters of the new function. The use of the wildcard ('*') hints at the idea that all parameters available for the function on the right-hand side of the assignment remain accessible by a user of the new function.

For example, given the following example function to define a gray color value

```
    color gray( float intensity = 0.5 ) {
        return color( intensity);
    }
```

the following function variants define different names for different intensities of gray while keeping the `intensity` parameter exposed for later adjustments:

```
    color light_gray(*) = gray( intensity: 0.8 );
    color dark_gray(*)  = gray( intensity: 0.2 );
```

The syntax of a function variant deviates from the function definitions from above in that it does not use a block of statements but an assignment-like expression referring to the underlying function call, which can refer to a regular function or to another function variant. Explicit arguments to this function call overwrite the default initializers, other parameters keep their initializers. The only eligibles expressions for the right-hand side are function calls or let-expressions, explained in Section 12.9.

A function variant has the same signature as the underlying function, i.e., parameters and return type are the same, except that those parameters that have received an argument in the right-hand side function call expression get those arguments as initializers, while others retain there original initializers, or none if the underlying function did not provide one for this parameter. A function variant can thus have more initializers than the underlying function, but it remains that parameters with default initializer must follow parameters without initializer in the resulting signature of a function variant.

For example, given the function definition

```
    float example_function( float a, color b = color(0), bool c = false) {
        ...
    }
```

the variant

```
    float example_variant(*) = example_function( c: true);
```

is equivalent to this function definition:

```
    float example_variant( float a, color b = color(0), bool c = true) {
        return example_function(a,b,c);
    }
```

Function variants define a new function. Function variants cannot be overloaded, neither by regular function definitions nor by other function variants.

The function call on the right-hand side expression can be subject to overload resolution, following the rules in Section 12.4. In contrast to regular function calls, it is legal for the call in a function variant to not provide arguments for parameters that have no initializers. An example is the parameter a in the `example_variant` function variant above.

Function variants cannot have size-deferred array types as return types.

Note: Function variants are a possibility to store a function call with parameters in an MDL file. An MDL editor application could use them to store nodes of a node-graph representation.

12.8 Placeholder return type specifier

The placeholder type specifier `auto` can be used as the return type of a function declaration since it can be automatically deduced from the return statement initializers or the functions defining expression (Section 12.6).

For example:

```
auto f() { return 0.0; }      // f has the return type float
auto g() = 1;                 // g has the return type int
```

A placeholder type specifier can be further restricted with a `uniform` or `varying` type modifier.

If a function contains multiple return statements, they must all deduce to the same type.

For example:

```
auto max(int a, int b) {
    if (a < b)
        return b;     // return type is int
    return a;         // return type is also int -- ok
}
```

If a function uses return type deduction, it cannot be redeclared using the type that it deduces to, even if it deduces to the same type.

12.9 Expression sharing in function definitions with let-expressions

let_expression   : let
                                   (*variable_declaration*
                                   | { *variable_declaration* {*variable_declaration*} }
)
                                 in *assignment_expression*

The expressions for initializers of function variant parameters can be complex or costly to evaluate. The sharing of such expressions or common sub-expressions is possible with *let-expressions*. They are applicable to function definitions using an expression (Section 12.6 and to function variants (Section 12.7).

A let-expression for function variants consists of a block of variable declarations and a final expression with the function call to the underlying function definition. The scope of the variables extends to the end of the let-expression, such that the final expression can make use of the variable values. In general, variables can also be used in subsequent definitions of other variables in the let-expression. A variable cannot be used in its own initializing expression. Variables are read-only and cannot be re-defined in the same let-expression.

The expressions in the let-expression can also reference the function parameters as read-only rvalues.

Variables in let-expression for function variants can be of any MDL type permitted for function parameters.

For example, the following function variant re-uses the result of a texture lookup for two arguments of the underlying function call:

```
color example(*)
  = let {
      color c = tex::lookup_color( texture_2d( "sample.png"), float2(0.5,0.5));
  } in
    example_color_function( value1: c, value2: c);
```

Note: Let-expressions in function variants are a possibility for an MDL editor application to store a node-graph representation in an MDL file preserving a directed-acyclic graph structure of a function call network instead of unrolling it to disconnected expression trees.

12.10   Operator functions

primary_expression	:	...
	|	operator *operator_function_op argument_list*
operator_function_op	:	[] | ! | ˜ | + | − | * | / | % | << | >> | >>> | < | <= | > | >= | == | !=
	|	& | ^ | | | && | || | ?

In addition to their usual call syntax from Section 6.5, operators can be called like functions by prefixing the operator with `operator` keyword.

For example:

```
int result = operator+(1,2);
```

Operator functions are not applicable for all operators. For example, increment, decrement, and assignment operators require an lvalue argument, which cannot be realized with the parameter-passing by value. The comma operator is excluded from operator function call syntax because its purpose is to sequence side-effecting operations and has no utility in declarative expressions. The left operand will be ignored and the operator removed by an optimizing compiler.

The list of applicable operators are the array access operator, all logical operators, all bitwise operators, all shift operators, all comparison operators, all arithmetic operators, and the ternary conditional operator.

The special properties of the ternary conditional operator and the binary logical operators about undefined argument evaluation (Section 6.5) is also true for their operator function call syntax.

All operators use `x` as their first parameter name and `y` as their second parameter name where applicable. Only exceptions are the array access operator and the conditional operator, which have for a given type $\mathcal{T}$ the following signatures:

```
𝒯 operator[]( 𝒯[] a, int i);
𝒯 operator?( bool cond, 𝒯 true_exp, 𝒯 false_exp);
```

The operator function call allows the use of named argument calls. All three calls in the following example are semantically identical:

```
int result1 = 1 + 2;
int result2 = operator+(1,2);
int result3 = operator+(x:1,y:2);
int result4 = operator+(y:2,x:1);
```

13   Materials

Materials are built around two concepts: the `material` type and *material definitions*. The `material` type has a few related types, among which the distribution functions are the central connection to the renderers to describe surface, emission and volume properties. The material definitions have a signature like a function returning a `material`, but their implementations differ fundamentally from function bodies.

Material definitions exist in two variants: the *encapsulating material definition* described in Section 13.5 and the *open material definition* described in Section 13.6.

Note: This section introduces the following keywords:

material   bsdf   edf   vdf   hair_bsdf

material_surface   material_emission   material_volume   material_geometry

They represent types and their use is restricted to what is described in this section and the standard module in Section 21. In particular, user-defined functions shall not have parameters, return types, or local variables using these types, and user-defined materials shall not have parameters using these types with the exception of the `material` type as detailed in Section 13.7.

13.1   The material type

The `material` type is defined as a built-in structure-like type with the following definition:

```
struct material {
  uniform bool      thin_walled = false;
  material_surface  surface     = material_surface();
  material_surface  backface    = material_surface();
  uniform color     ior         = color(1.0);
  material_volume   volume      = material_volume();
  material_geometry geometry    = material_geometry();
  hair_bsdf         hair        = hair_bsdf();
};
```

Primary material definition.

thin_walled – If false, surfaces are treated as interface between two volumes and the `ior` and `geometry` fields describe properties of the enclosed volume. If `true`, surfaces are treated as double-sided and enclose an infinitely thin volume. In the thin-walled case, front and back side use both the front side material if the BSDF and EDF of the `backface` field are left at their default values. Otherwise the back side uses the description provided with the `backface` field. If different materials are used for the front face and the back face, both materials should have equal transmission interactions.

surface – Front surface reflection, refraction and emission characteristics. Also used for the back surface if `thin_walled` is `true` and the BSDF and EDF of the `backface` field are left at their default values.

backface – Back surface reflection, refraction and emission characteristics if `thin_walled` is `true` and if either the BSDF or the EDF contained in this field is set to a non-default value. Otherwise this field is ignored.

ior – Index of refraction used in front and back surface transmission interactions.

volume – Scattering, absorption, and emission of light within the participating medium in a volume.

geometry – Controls for geometric manipulations of the object surface.

    hair – Hair BSDF describing the aggregated reflective and transmissive scattering of incoming light for hair primitives.

The `material` type enables three categorial different materials with respect to how they interpret surfaces:

1. A surface is an interface between volumes.

2. A surface represents a thin wall enclosing conceptually an infinitely thin volume with identical materials on both sides, for example, window glass can be modeled this way.

3. A surface represents a thin wall with different materials on both sides, in which case both materials should have equal transmission interactions or otherwise this can give rise to inconsistencies in bidirectional techniques and should be reported as a warning if it can be reliably detected.

All cases and the corresponding settings of the different fields in the material description are described in the following table:

field name	interface	thin wall with equal sides	thin wall with different sides
thin_walled	false	true	true
surface	used for both sides[†]	used for both sides[†]	used for front side
backface	ignored	must be set to defaults	used for backside
ior	used	used but no refraction	used but no refraction
volume	used for enclosed volume	ignored	ignored
geometry	used once with front-side orientation for both sides		
hair	not affected		

[†]**Note:** In the first two cases where `surface` is used for both sides, the EDF contained in `surface` is only used for the front side and not for the back side. There is no emission on the back-side unless an EDF is specified with the `backface` field and `thin_walled` is set to `true`.

The `material` type shares the properties of structure types to construct values using constructors and to access fields using the dot-operator. It can be used in other structure types, arrays, or type definitions, but those are then also subject to the restrictions that apply to the `material` type.

13.2 Distribution function types: bsdf, edf, vdf, and hair_bsdf

Light interaction with objects is divided into four categories to describe reflection and transmission by a surface, emission of light by a surface, dispersal and absorption within a volume, and reflection and transmission by a hair primitive. Collectively, these properties are defined by four data types in MDL:

    bsdf – A *bidirectional scattering distribution function* (BSDF) that describes the interaction of light with the surface. The default constructor `bsdf()` creates a non-scattering, i.e., black BSDF.

    edf – An *emission distribution function* (EDF) that describes the light-emitting properties of the surface. The default constructor `edf()` creates a non-emitting, i.e., black EDF.

    vdf – A *volume distribution function* (VDF) that describes the scattering and absorption of light in a volume. The default constructor `vdf()` creates an isotropic VDF.

hair_bsdf – A *hair bidirectional scattering distribution function* (hair BSDF) that describes the aggregated interaction of light with the strand of a hair primitive. The default constructor `hair_bsdf()` creates a non-scattering, i.e., black hair BSDF.

MDL defines a standard set of distribution functions based on these types for use in constructing the components of a material. These distribution functions are described in Section 21.

The distribution functions are defined in the `df` module of MDL. In the examples that follow in Section 13.4, distribution function names are prefixed by the `df::` name qualifier (for example, in `df::diffuse_reflection_bsdf`).

13.3   Compound types in the fields of the material

The four fundamental properties of the `material` type—for the surface, volume, emission, and geometric characteristics of objects — are represented by `struct` types. These structs contain fields that specify instances of distribution functions.

One field in the emission property uses the following built-in enumeration type:

```
enum intensity_mode {          This mode determines the measure used for the emission intensity.
    intensity_radiant_exitance,
    intensity_power
};
```

The four `struct` types for the fundamental properties of the `material` type are:

```
struct material_surface {
  bsdf              scattering = bsdf();
  material_emission emission   = material_emission();
};
```

Surface properties of the material model.

scattering − BSDF describing the reflective and/or transmissive scattering of incoming light.

emission − Light emission properties of the material defined by a struct that contains both the EDF and an intensity factor.

```
struct material_emission {
  edf                   emission  = edf();
  color                 intensity = color(0.0);
  uniform intensity_mode mode     = intensity_radiant_exitance;
};
```

Emission properties of the material model.

emission − The emission distribution function.

intensity − Scaling factor for the result of the emission distribution function. For local EDFs, this is the radiant exitance if `mode` is set to `intensity_radiant_exitance` (the default), or power if `mode` is set to `intensity_power`.

mode − The measure used for the `emission` parameter.

```
struct material_volume {
  vdf   scattering             = vdf();
  color absorption_coefficient = color();
  color scattering_coefficient = color();
  color emission_intensity     = color();
};
```

Volume properties of the material model.

scattering	–	VDF describing the scattering of light within the participating medium.
absorption_coefficient	–	The probability density (per meter in world space) of light being absorbed by the participating medium.
scattering_coefficient	–	The probability density (per meter in world space) of light being scattered from its current direction.
emission_intensity	–	Uniform light emission in the volume given as radiance per distance traveled through the medium in $\left[\frac{W}{m^3 sr}\right]$.

```
struct material_geometry {
  float3 displacement   = float3(0.0);
  float  cutout_opacity = 1.0;
  float3 normal         = state::normal();
};
```

Geometric properties of the material model.

displacement	–	Vector defining direction and distance of position modification of current surface position in internal space.
cutout_opacity	–	A value between 0.0 and 1.0 for a cutout mask, where for a value of 0.0 the object geometry is ignored and for a value of 1.0 the object geometry is there.
normal	–	Surface normal vector in internal space to use for all calculations at the current surface position.

The different material fields are in principle evaluated independently and at the renderer algorithms sole discretion. The evaluation of the fields in the `material_geometry` structure though have the potential to change the renderer state described in Section 19, for example, `state::normal`, and thus can influence the evaluation results of other fields that are evaluated later. The relevant evaluation orders are as follows: The geometry fields are evaluated before all surface fields. Within the geometry fields, `displacement` is evaluated first, `cutout_opacity` second, and `normal` last.

Other fields of the MDL material, such as `ior`, `volume`, or `geometry`, do not influence hair shading.

The `float3` vectors of the `material_geometry` structure are defined in the internal space of the renderer. The state functions for coordinate space transformations, see Section 19.2, allow the use of object-space or world-space dependent values for those vectors. Note though that a world-space dependency can have negative performance and memory impact on renderers that support object instancing because multiple instances with a shared object might have different displacements in world coordinates and can no longer be shared.

13.4   Instantiating a material

postfix_expression	:	*primary_expression*
		$\{$...
		$\mid$ *argument_list*
		$\}$
argument_list	:	(
		$[$*named_argument* $\{$, *named_argument*$\}$
		$\mid$ *positional_argument* $\{$, *positional_argument*$\}$
		$\{$, *named_argument*$\}$
		$]$
		)

The `material` type can be used to define a material in a syntactic form that resembles a structure type constructor including positional and named arguments. For example, to create a diffuse green material, the `surface` field of the `material` struct is defined as a `material_surface` struct in which the BSDF is tinted green.

```
material(
    surface : material_surface(
                scattering : df::diffuse_reflection_bsdf(
                        tint : color( 0.5, 1.0, 0.5)
                        )
            )
)
```

In this example, the value of the `scattering` parameter to `material_surface` is a `bsdf` from the standard MDL module `df` (see Section 21.1.1).

Material instantiations are used in material definitions, which are explained in the next two sections.

13.5   Encapsulating material definitions

function_declaration	:	...
	$\mid$	*type* $[$*annotation_block*$]$ *simple_name*
		parameter_list $[$*annotation_block*$]$ = *expression* ;
parameter_list	:	($[$*parameter* $\{$, *parameter*$\}$ $[$,$]]$)
parameter	:	*type simple_name* $[$= *assignment_expression*$]$
		$[$*annotation_block*$]$

A material definition gives a name to a specific material instance. In addition, a material definition can define input parameters that can be used as rvalues within the material instantiation in expressions and function-call arguments to initialize properties of the material model or of other already existing materials. Parameterizing a material definition enables the encapsulation and customization of materials to create custom material libraries. This parameterization can be thought of as analogous to the definition of a function.

Technically, a material definition is a function definition with a, possibly empty, parameter list that returns a material. The parameter types are restricted to those allowed for function parameters plus the `material`

type, see Section 13.7 for its use. In particular, material parameters shall not be of type `bsdf`, `edf`, `vdf`, `hair_bsdf`, `material_surface`, `material_volume`, `material_emission`, or `material_geometry`.

Deviating from function definitions is the implementation of the material definition. Instead of a function body, a material definition requires an assignment from an expression of type `material`. This can be an instantiation of the `material` structure type itself, the result of another material definition, or a let-expression as explained in Section 13.8.

The following example uses the previous material instance for a diffuse green material and gives it a name without parameters:

```
material green_material()
  = material(
      surface : material_surface(
                  scattering : df::diffuse_reflection_bsdf(
                              tint : color( 0.5, 1.0, 0.5)
                            )
                )
    );
```

The following example extends the previous example to a more generic diffuse material with a `tint` parameter in the signature. The `tint` parameter input is used to set the equally-named `tint` parameter of the `df::diffuse_reflection_bsdf`:

```
material diffuse_material( color tint = color( 1.0))
  = material(
      surface : material_surface(
                  scattering : df::diffuse_reflection_bsdf(
                              tint : tint
                            )
                )
    );
```

Given this parameterization of `tint` in `diffuse_material`, the `green_material` definition—using `diffuse_material` in a syntactically identical manner to calling a function—can be defined instead as:

```
material green_material( )
  = diffuse_material( color( 0.5, 1.0, 0.5));
```

The `tint` parameter has been bound by the encapsulation, and is inaccessible by a user of `green_material`.

13.6   Open material definition (material variant)

function_declaration	:	...
	|	*type* [*annotation_block*] *simple_name*
		(*) [*annotation_block*] = *expression* ;

An *open material definition* functions in the same manner as the encapsulation of the previous example. However, parameters are not encapsulated in this definition. The use of the wildcard ('*') hints at the idea that all parameters available for the material on the right-hand side of the assignment remain accessible by a user of the new material definition.

Open material definitions can be used to define a family of materials from one material definition using different default values for its parameters. The parameters remain accessible for later adjustments. Open material definitions are also called *material variants* and are very similar to function variants from Section 12.7.

For example, if the green material is defined as an open material definition as follows:

```
material green_material( * )
  = diffuse_material( color( 0.5, 1.0, 0.5) );
```

Then, a user of the green material can define another diffuse material based on the green material changing its tint, for example, to a light green material. This example uses again an open material definition, which leaves the `tint` parameter accessible:

```
material light_green_material( * )
  = green_material( color( 0.7, 1.0, 0.7) );
```

Such a refinement of an open material definition can also be done using an enclosing material definition.

13.7 Materials as material parameters

Material parameters can be of type `material`, which enables generic adaptor materials and the re-use of materials and material components in other materials. The components of a `material` parameter are accessed in the material definition using the dot notation for the fields of the material.

The following example provides a generic adaptor that takes a material and returns the equivalent thin-walled material with identical front-face and back-face material properties:

```
material thin_walled_material( material base)
  = material(
      thin_walled : true,
      surface     : base.surface,
      volume      : base.volume,
      geometry    : base.geometry
    );
```

The next example provides a generic material that adds a clear-coat layer to another material. Technically, this example adds a specular reflective layer with a Fresnel blend over the base material. The Fresnel blend is influenced through an additional `ior` parameter.

```
material add_clear_coat( float    ior,
                         material base )
  = material(
      volume   : base.volume,
      geometry : base.geometry,
      surface  : material_surface(
                   emission   : base.surface.emission,
                   scattering : fresnel_layer(
                                  layer : specular_bsdf(),
                                  base  : base.surface.scattering,
                                  ior   : ior
                                )
                 )
    );
```

13.8   Expression sharing in material definitions with let-expressions

let_expression	:	`let`
		(*variable_declaration*
		| { *variable_declaration* {*variable_declaration*} }
		)
		`in` *assignment_expression*

Material definitions can become deeply nested as parameters take further material definitions as values and they may contain common subexpressions without the ability to share them. A *let-expression* can help to improve both aspects; more structural flexibility in describing material definitions and shared common subexpressions.

A let-expression for encapsulating or open material definitions consists of a block of variable declarations and a final expression of type `material`, which becomes the result of the let-expression. The scope of the variables extends to the end of the let-expression, such that the final expression can make use of the variable values. In general, variables can also be used in subsequent definitions of other variables in the let-expression. A variable cannot be used in its own initializing expression. Variables are read-only and cannot be re-defined in the same let-expression.

The expressions in the let-expression can also reference the material parameters as read-only rvalues.

Variables in let-expression can be of any MDL type including `material`, `bsdf`, `edf`, `vdf`, `hair_bsdf`, `material_surface`, `material_emission`, `material_volume`, or `material_geometry`.

For example, the `add_clear_coat` material defined in the previous section can be rewritten using variables in a let-expression to clarify the construction of the `surface` input to the material:

```
material add_clear_coat( float    ior,
                         material base)
  = let {
      bsdf coat = specular_bsdf();
      bsdf coated_scattering = fresnel_layer(
                        layer : coat,
                        base  : base.surface.scattering,
                        ior   : ior
                     );
      material_surface coated_surface(
                        emission   : base.surface.emission,
                        scattering : coated_scattering
                     );
    } in
      material(
        volume   : base.volume,
        geometry : base.geometry,
        surface  : coated_surface
      );
```

Note that the `bsdf` variable `coat` is used as the value of the `layer` parameter in `fresnel_layer`.

13.9   Conditional expressions for materials

conditional_expression	:	*logical_or_expression* [? *expression* : *assignment_expression*]

Conditional expressions with the ternary conditional operator ('?') can be used in expressions of type `material`, `material_surface`, `material_emission`, `material_volume`, `material_geometry`, `bsdf`, `edf`, `vdf`, or `hair_bsdf` under the restriction that the first operand is uniform.

Such conditional expressions can for example be used to implement a material switcher that, depending on a Boolean input parameter, selects one or the other material:

```
material switch_material( uniform bool condition,
                          material     m1,
                          material     m2)
  = condition ? m1 : m2;
```

14 Annotations

annotation_declaration   :   `annotation` *simple_name parameter_list* [*annotation_block*] `;`

MDL defines a mechanism called annotations to attach metadata to various components of a material or function, as well as the material or function itself, or another annotation declaration.

Annotations must be declared before they are used. An unknown or wrongly typed annotation shall issue a warning and will be suppressed.

An annotation is declared globally using the `annotation` keyword followed by the name of the annotation, optional annotation parameters surrounded in parenthesis, and an optional annotation block at the end. Annotation parameters can have default initializers with constant expressions as values.

For example:

```
annotation annotation_example( float f, string s = "");
```

This declares an annotation named `annotation_example` which accepts a `float` and a `string` parameter.

Annotations are a part of the module where they are defined and they share the name space with other MDL identifiers, such as functions.

An annotation can be declared multiple times, called *annotation overloading*, provided the overloads differ at least by the number or types of their parameters. This is similar to function overloading and overload resolution is defined for annotations analogously to function overload resolution in Section 12.4.

14.1   Annotation application

annotation_block   :   `[[` *annotation* { `,` *annotation* } [`,`] `]]`

annotation   :   *qualified_name argument_list*

qualified_name   :   [[`::`] *module_name* `::`] *simple_name*

Annotations can be applied to:

- Modules
-
- Material definitions
- Function declarations
- Parameters and return types of materials and functions
- Annotation declarations
- Structure types and their fields
- Enumeration types and their values
- Constants and variable declarations
- Variables in let-expressions

Annotations are placed in blocks immediately after the declaration they are annotating, and before the opening curly brace for function definitions, structure type or enumeration type annotations. The comma-separated list of one or more annotations is enclosed in double brackets. The list of annotations can end with a trailing comma. An individual annotation looks like a function call with no return value where the name of the function is the annotation and the arguments are values associated with the annotation. These

values need to be constant expressions. The annotation syntax includes positional and named arguments explained for functions in Section 12. It is not an error to have several annotations of the same name.

An annotation block has the following form:

```
[[
    annotation_name(param1, param2, ...),
    annotation_name(param1, param2, ...),
    ...
]]
```

The `annotation_example` declared above can be used to annotate a material parameter as follows:

```
material material_example(
    color c  [[ annotation_example( 1.5, s : "a string") ]]
)
  = material(...);
```

Annotations can be used to attach any type of metadata, though the common case is metadata to describe the user interface for a material or material parameter, see also the standard annotations in Section 18.

Note: The double brackets used for annotation blocks, `[[` and `]]`, are not tokens in MDL to avoid problems with a possible occurrence of `]]` for nested array accesses. Nonetheless, annotations require that the double brackets are not separated by any other characters including white spaces.

15 Modules and packages

In MDL, all identifiers and all typenames live in modules with the exception of the types available as built-in reserved words. A module defines a namespace. Declarations inside a module need to be marked for export before they can be used outside of the module, and other modules need to import those declarations before they can be used.

A module corresponds one-to-one to an MDL source file. The name of the module is the name of the source file without the `.mdl` file extension.

Because of the correspondence of module names to file names and package names to directory names, these names are allowed to consist of arbitrary Unicode code points. Module and package names that are valid MDL identifiers are referred to directly by their name. Module and package names that are not valid MDL identifiers are represented by *Unicode identifiers* as defined in Section 5.6.

Modules can be used as such or they can be organized in packages. A package corresponds one-to-one to a directory containing module source files. Packages can be nested. The name of the package is the name of the directory.

15.1 Import declarations

import	:	import *qualified_import* { , *qualified_import* } ;
		| [export] using *import_path*
		import (* | *simple_name* { , *simple_name* }) ;
import_path	:	({ .. :: } | [. ::] | [::]) *module_name*
qualified_import	:	*import_path* :: (* | *simple_name*)
module_name	:	*path_identifier* { :: *path_identifier* }
path_identifier	:	*unicode_identifier* | *simple_name*
simple_name	:	*IDENT*

A module can import individual or all declarations from other modules with import declarations, which must be specified after the version declaration (see Section 4.1) and must be specified before all other declarations.

Depending on the particular form of the import declarations used, the imported declarations can only be referred to by their qualified identifiers or by their unqualified identifiers. A qualified identifier is formed by the identifier of the imported module including its optional package name, the scope operator '::', and the unqualified identifier of the declaration. Declarations that can be referred to by their unqualified identifier can also be referred to by their qualified identifier.

The following table illustrates the four different forms of the import declaration. For the example code, it assumes a module `m` with three declarations `a`, `b`, and `c`, and a module `n` with a declaration `d`. For the sake of the illustration here, those declarations can be for example materials or functions.

Import declaration	Accessible declarations	Description
`import m::*, n::*;`	`m::a, m::b, m::c, n::d`	Qualified import of all declarations from the specified modules.
`import m::a, m::b, n::d;`	`m::a, m::b, n::d`	Qualified import of selected declarations only. Other declarations from the specified modules are inaccessible unless imported through an additional import declaration.
`using m import *;`	`a, b, c, m::a, m::b, m::c`	Unqualified import of all declarations from a module. Only one module can be specified in an unqualified import declaration.
`using m import a, b;`	`a, b, m::a, m::b`	Unqualified import of selected declarations only. Only one module can be specified in an unqualified import declaration.

It is not an error if the same declaration is imported more than once.

The following example illustrates how a qualified import of all declarations is combined with the unqualified import of selected declarations using the same module `m` from above:

```
import m::*;
using m import a, b;
// accessible declarations are: a, b, m::a, m::b, m::c
```

It is an error if a declaration of the same name is imported in the unqualified form from two different modules.

A module must not import itself and the import-graph of all modules in a system must not contain any cycles.

The module name can be optionally preceded by a sequence of package names separated by the scope operator ':: ', which forms a *relative package path*. Adding the scope operator ':: ' to the beginning of a relative package path changes it to an *absolute package path*. A relative package path can also use a sequence of parent package identifiers using the two dots '..' notation, or start with explicitly referring to the current package with the single dot notation '.'. There can only be as many parent package identifiers as the importing module has parent packages itself.

Qualified identifiers from modules in packages require the qualification with all package names and the module name as given in the import declaration, all separated by the scope operator ':: '. Parent package identifiers ('..') as well as current package identifiers ('.') will be omitted in the qualified identifiers.

The following example illustrates parent package identifiers and the resulting qualified identifiers. A module in the package P1 imports another module M from a package P2 that is located next to P1:

```
import ..::P2::M::example_material;
//
// the qualified name of the example_material is now
// P2::M::example_material
```

Package and module names live in a separate namespace. In case of ambiguities other declarations are preferred over a module.

Relative and absolute package paths are translated to relative and absolute file paths, respectively, by changing the scope operator ':: ' to the forward slash '/' and appending the `.mdl` file extension.

Modules are located in the file system using the file path search on their respective file path as defined in Section 2.2.

15.2   Export declarations

mdl	:	*mdl_version*
		{ *import* }
		[module *annotation_block* ;]
		{[export] *global_declaration* }

import	:	import *qualified_import* { , *qualified_import* } ;
	|	[export] using *import_path*
		import (∗ | *simple_name* { , *simple_name* }) ;

All declarations of a module are private to that module unless they are prefixed with the export qualifier.

For example:

```
int private_function_example() {    // not visible outside of module
    return 1;
}

export int function_export_example() {  // visible outside of module
    return private_function_example();
}
```

For function overloads, either all overloaded versions have an export qualifier or none.

Parameter types and identifiers in default initializers of parameters of exported functions must be exported as well. This ensures their accessibility in modules importing such functions. However, a module importing such functions may not necessarily need to import all types, unless it uses those parameters and does not rely on their defaults, and it may not need to import identifiers of default initializers, unless it uses them explicitly. Furthermore, it is sufficient if such types and identifiers are exported by some module, which must not be the same module as the one exporting the function. This is necessary for identifiers that are imported in their qualified form from another module and cannot be re-exported.

Return types of exported functions must also be exported by some module (or be one of the builtin types). Modules importing a function also need to import its return type if they call the function or use the type otherwise.

Imported declarations can be exported again if they are imported in their unqualified form. The unqualified imported declaration is part of the importing modules namespace. Exporting it makes it only visible from this namespace and not from its originating modules namespace.

For example a module p exports two declarations from the module m, which is defined as above:

```
// module p
export using m import a, b;
```

Another module can now import p::a and p::b without knowing about module m. For example:

```
// module example
using p import a;
import p::b;
// accessible declarations are: a, p::a, p::b
// while m::a and m::b remain inaccessible
```

A module can import the same declaration from different modules without problems:

```
// module example
```

```
import m::a, p::a;
// accessible declarations are: m::a, p::a
```

An export of an imported declaration does not create a new declaration. This is relevant for types and their use to distinguish among function overloads, where an export of an imported type does not constitute a new type. In continuation of the previous example with the assumption that `m::a` is a type, the following function overloads will cause an error because `m::a` is not a different type than `p::a`:

```
int function_overload( m::a parameter);
int function_overload( p::a parameter); // ! error
```

It further remains an error to import the same declaration in its unqualified form from two different modules even though one is only an export of the other. The following example illustrates this error:

```
// module example with error
using m import a;
using p import a; // ! error because a is imported a second time in
//    unqualified form from a different module
```

15.3   Interaction with function overloads

If a module imports an identifier referencing a function, all overloads of that function are imported. If the identifier is imported in its unqualified form, the module may add further overloads of that function. If the identifier is exported from the importing module, all overloads from the imported module as well as the added overloads must be exported.

Adding overloads to an imported function never alters the behavior of the imported overloads, or any other imported function. For example, if an imported function `a` calls another function `b`, the behavior of `a` cannot be changed by adding additional overloads to `b`.

15.4   Interoperability of modules of different language versions

Modules that are implemented using a different language version of MDL can nonetheless be freely mixed with the following restrictions:

1. If a module imports declarations from another module, both modules need to use a language version with the same major version number.

2. If a module imports declarations from another module, those declarations must be legal in the language version of the importing module. In particular, the name of the declared entity, its signature, parameter names and default initializer must all be legal.

The second restriction enables forward and backwards compatibility to the extent possible. As an example, the standard modules of MDL 1.1 contain extensions, like a new distribution function, that cannot be imported into an MDL 1.0 module while the other declarations that came from MDL 1.0 continue to be available for MDL 1.0 module imports.

15.5   Package structure with lead module

As an example, the module system with its package search allows the packaging of materials and functions in a library of implementation modules underneath a package directory and a lead module of the same name as the package at the same level as the package directory. The lead module can import all publicly relevant declarations from the implementation modules and export them.

The directory and module structure for a module and package `m` with implementation modules `i1`, `i2`, and `i3` would look like this:

```
<search-path-root>
```

```
    +--- m.mdl
    +--- m
         +--- i1.mdl
         +--- i2.mdl
         +--- i3.mdl
```

An example for the lead module `m` in the file `m.mdl` would be:

```
// lead module m
export using m::i1 import public_material_1;
export using m::i2 import public_material_2;
export using m::i3 import public_material_3;
```

15.6   Annotations on modules

mdl	:	*mdl_version*
		{ *import* }
		[`module` *annotation_block* `;`]
		{[`export`] *global_declaration* }

Annotations can be applied to modules, e.g., display name, version or dependency annotations.

The optional place for annotations in modules is uniquely marked with the reserved word `module` followed by an annotation block and terminated with a semicolon (';'). Module annotations follow the import block (needed to declare the annotations used) and precede all other declarations.

16   Standard modules

MDL requires the following set of standard modules to be available.

An import declaration with a standard module name shall always import these standard modules, which means, modules stored under the same fully qualified name cannot be imported, they are shadowed by the standard modules. The standard modules behave as if they are stored in an implicit and always present search path of highest priority (see Section 2.2).

Note: Modules with the same unqualified name as a standard module, e.g., `my_package::math` are possible and can be imported as any other module. It is thus recommended to use absolute import paths when importing standard modules.

The standard MDL modules are:

`std`	imports all other standard modules and re-exports all declarations.	
`limits`	standard global constants for MDL limits.	cf. Section 17
`anno`	standard annotations.	cf. Section 18
`state`	standard renderer state functions.	cf. Section 19
`math`	standard library math functions and constants.	cf. Section 20.1
`tex`	standard library texture functions.	cf. Section 20.3
`scene`	standard library scene data lookup.	cf. Section 20.4
`debug`	standard library debugging functions.	cf. Section 20.5
`df`	standard elemental distribution functions, modifiers, and combiners.	cf. Section 21

The standard `std` module allows to import all standard modules at once and use their declarations with in the `std` scope. For example:

```
import ::std::*;

float stdlib_example() {
    return std::sin( std::HALF_PI);
}
```

17 Standard limits

The following standard global constants for some limits in MDL are made available through the standard limits module (Section 16). For example, the limits module can be imported as any other module and all the regular scoping and shadowing rules apply:

```
import ::limits::*;
```

const float FLOAT_MIN = 1.17549435E-38f		The smallest positive normalized `float` value.
const float FLOAT_MAX = 3.40282347E+38f		The largest `float` value.
const double DOUBLE_MIN		The smallest positive normalized `double` value supported by the current platform.
const double DOUBLE_MAX		The largest `double` value supported by the current platform.
const int INT_MIN = -2147483648		The smallest `int` value.
const int INT_MAX = 2147483647		The largest `int` value.

18 Standard annotations

MDL defines a set of standard annotations to attach metadata to various elements of declarations and definitions in MDL.

Annotations need to be declared before they can be used, see Section 14. The standard annotations are declared in the standard `anno` module (Section 16). For example, the `anno` module can be imported as any other module and all the regular scoping and shadowing rules apply:

```
import ::anno::*;
```

The following are the provided standard annotations to represent common metadata:

`soft_range(int  min, int  max)`
`soft_range(int2 min, int2 max)`
`soft_range(int3 min, int3 max)`
`soft_range(int4 min, int4 max)`
`soft_range(float  min, float  max)`
`soft_range(float2 min, float2 max)`
`soft_range(float3 min, float3 max)`
`soft_range(float4 min, float4 max)`
`soft_range(double  min, double  max)`
`soft_range(double2 min, double2 max)`
`soft_range(double3 min, double3 max)`
`soft_range(double4 min, double4 max)`
`soft_range(color min, color max)`
	Specifies a range of useful values for the parameter, however the parameter value can exceed this range. Vector values are compared component-wise.
	
	min – The minimum value of the range.
	
	max – The maximum value of the range.

`hard_range(int  min, int  max)`
`hard_range(int2 min, int2 max)`
`hard_range(int3 min, int3 max)`
`hard_range(int4 min, int4 max)`
`hard_range(float  min, float  max)`
`hard_range(float2 min, float2 max)`
`hard_range(float3 min, float3 max)`
`hard_range(float4 min, float4 max)`
`hard_range(double  min, double  max)`
`hard_range(double2 min, double2 max)`
`hard_range(double3 min, double3 max)`
`hard_range(double4 min, double4 max)`
`hard_range(color min, color max)`
	Specifies bounds for the parameter that cannot be exceeded. Vector values are compared component-wise.
	
	min – The minimum value of the range.
	
	max – The maximum value of the range.

`display_name( string name)`	Specifies a name to use when the element is displayed in a user interface.

```in_group(string group, bool collapsed = false) in_group(string group, string subgroup, bool collapsed = false) in_group(string group, string subgroup, string subsubgroup, bool collapsed = false)```	Specifies that an element is in a group or nested subgroup for presentational purposes in a user interface. Its recommended use is for functions, materials, and their parameters. The optional `collapsed` parameter controls the state of a group (or subgroup) in a user interface that can collapse or expand groups. A group that contains parameters is now collapsed if at least one of its parameters has the collapsed parameter set to `true`. A group that has no parameters but subgroups is now collapsed if all of its subgroups are collapsed. In all other cases a group is expanded.
```ui_order(int order)```	Specifies the order in which a user interface should present the elements. Elements with lower order values should be displayed first. The default order value is zero and a group has the smallest order value of its contained elements or subgroups. Elements of equal order values remain in their order of definition. Its recommended use is for functions, materials, and their parameters.
```enable_if(string condition)```	Specifies that an input parameter only has an effect if the Boolean expression given by the `condition` string evaluates to true. If it evaluates to false, a user interface could, for example, gray out the representation of the input parameter and disable editing it. The `condition` may also evaluate to the symbolic *not-a-value* (NaV) representation, in which case an integration should not disable parameter editing. An integration may have only limited parsing or evaluation capabilities for the condition string. If it fails to parse or evaluate the condition, it shall use NaV as the evaluation result. Also the condition may not be evaluable, if it depends on varying state properties. The *condition* string is a string literal containing an *enable-if-condition*, which is a restricted MDL *expression* (Section 6.5) where each sub-expression is: • a constant expression (Section 6.7), • the name of another parameter of the same function or material definition, whose type must be one of the types permitted for constant expressions (Section 6.7), `texture_2d`, `texture_3d`, `texture_cube`, `texture_ptex`, `light_profile`, or `bsdf_measurement`, • a call to one of the functions in the standard math module (Section 20.2), • a call to one of the `tex::texture_isvalid` functions (Section 20.3), the `df::light_profile_isvalid` function (Section 21.2), or the `df::bsdf_measurement_isvalid` function (Section 21.1.4), or

- one of the built-in operators "&&", "||", "<", "&", "|", "^", "<=", "==", "!=", ">=", ">", "<<", ">>", ">>>", "+", "−", "*", "/", "%", "!", "~", ".", or "[]".

The references to other parameters of texture, light profile, or measured BSDF type can only be used as an argument to the respective isvalid-functions.

The expression is evaluated like an MDL expression. A parameter name evaluates to its current literal value, or NaV if it has none, for example, if it is connected to a non-constant function call result. The result of an expression becomes NaV, if one of its operands is NaV, except for the following evaluations of the && and || operators: false && NaV becomes false, NaV && false becomes false, true || NaV becomes true, and NaV || true becomes true.

Example annotations are:

```
anno::enable_if("is_transparent")
anno::enable_if("is_transparent==true && transparency>0")
```

Note: This annotation is a hint to the integration. It is not a requirement for a compiler to check if the condition corresponds to the actual dependencies in the MDL program code.

`hidden()`	Specifies that the element should not be visible in an application's user interface.
`description(` `string description)`	Specifies a description of the element. An application providing a user interface for the element can use this text to provide a more detailed description beyond the display name.
`thumbnail(` `string name)`	Specifies a preview image for a material or a function. The parameter `name` needs to contain a valid file path as defined in Section 2.2, which needs to reference an image file in the JPEG or PNG file format as defined in Section 2.3. A square image resolution of a minimum of 256×256 pixel is recommended.
`author(` `string name)`	Specifies the name of the element author. Multiple authors are specified with multiple annotations. Its recommended use is for modules, functions, and materials.
`contributor(` `string name)`	Specifies the name of a contributing element author. Multiple contributors are specified with multiple annotations. Its recommended use is for modules, functions, and materials.
`copyright_notice(` `string copyright)`	Specifies copyright information.

`created(`
    `int    year,`
    `int    month,`
    `int    day,`
    `string notes)`
	Specifies the date on which an element was created along with a string to hold creation notes.

| ```
modified(
    int    year,
    int    month,
    int    day,
    string notes)
``` | Specifies a date on which an element was modified along with a string to hold notes related to the modification. |
| ```
version(
    int    major,
    int    minor,
    int    patch,
    string prerelease = "")
``` | Specifies the version of a module following the Semantic Versioning 2.0.0 [4], omitting build metadata. |
| ```
dependency(
    string module_name,
    int    major,
    int    minor,
    int    patch,
    string prerelease = "")
``` | Specifies a dependency of the module's contents on another module named `module_name` following the naming convention of the import declarations (see 15.1). The other module needs to be part of an import statement. Multiple dependency annotations are used to express multiple dependencies. A compiler or runtime shall issue a warning for modules whose dependencies are not satisfied. |

The version `major.minor.patch-prerelease` specifies the minimum version, following the Semantic Versioning 2.0.0 [4], that the referenced module must have to satisfy the dependency. In particular, the dependency is satisfied if the referenced module's version has the same major number and its minor number, patch number, and pre-release modifier compare equal or higher to the version requested.

For example, a module `pkg/example.mdl` with this version annotation

```
anno::version( 2, 1, 3)
```

works fine for modules that have dependency annotations as follows:

```
anno::dependency(   "pkg::example", 2, 0, 1)
anno::dependency( "::pkg::example", 2, 1, 3)
```

And it warns with modules that have dependency annotations as follows, one for a too high version number and one for a non-matching major number:

```
anno::dependency(   "pkg::example", 2, 1, 4) //!  warn
anno::dependency( "::pkg::example", 1, 1, 3) //!  warn
```

The standard libraries have no version annotation. They are implicitly versioned by the MDL language version and cannot be listed in module dependency annotations.

| ```
key_words(
    string[] words)
``` | Specifies a list of keywords related to an element material or function. Its recommended use is for functions and materials. These keywords can be used to search libraries of materials or functions. |

`unused()`
`unused(`
   `string description)`
	Specifies that the annotated element is not used in the implementation. This can be used to suppress compiler warnings about unused elements. The variant with the `description` text can be used to give an additional explanation why the element is not used, such as `"deprecated"` or `"reserved for future use"`, which may be shown in user interfaces.

`deprecated()`
`deprecated(`
   `string description)`
	Specifies that the annotated element is deprecated. This can be used in an application and by the compiler to warn a user about the use of deprecated elements. The variant with the `description` text can be used to give an additional explanation.

`usage(` `string hint)`	Provides usage hints on material and function return types and parameters . Multiple hints can be provided with multiple annotations. A user interface can offer preferred functions for the connection to a parameter if the function return type has a hint in common with the parameter or it can offer a more customized user interface control for parameter editing.

The following list defines recommended usage hints, but systems can choose arbitrary usage hints:

Usage hint	Type	Description
`anisotropy`	float	the range from 0.0 to 1.0 goes from no to full anisotropy
`anisotropy_rotation`	float	the range from 0.0 to 1.0 defines a full turn
`base_color`	color	base color
`density`	float	strength of volumetric scattering and absorption effects
`diffuse_color`	color	diffuse color
`displacement`	float / float3	distance for displacement mapping
`displacement_scale`	float	scale for displacement mapping
`emission_color`	color	emission color
`glossiness`	float	glossiness
`ior`	float / color	index of refraction
`metalness`	float	ratio of metallic vs dielectric behavior
`normal`	float3	normal vector for normal mapping
`roughness`	float	surface roughness of glossy contribution
`occlusion`	float	baked occlusion
`opacity`	float	opacity
`transparency`	float	transmission
`specularity`	float	amount of specular contribution
`specular_color`	color	specular color
`transmission_color`	color	transmission color
`uv`	float2 / float3	uv coordinate
`volume_color`	color	volumetric color

`origin(` `string name)`	Used on copied, cloned, or otherwise refactored declarations to reference the original declaration. It is applicable on material definitions, function declarations, annotation declarations, structure type declarations, enumeration type declarations, or constant declarations. The original declaration is specified with its fully qualified name. Note that the name does not include the full signature, such as in the case of materials, functions, or annotations. **Note:** The MDL Encapsulated file format (Section 25) uses this annotation to refer to the original declarations of the encapsulated elements.

`enum node_port_mode {`
    `node_port_value_only,`
    `node_port_fields_only,`
    `node_port_value_and_fields`
`};`
	A node graph representation uses ports for inputs and outputs. Values of the node port mode can be used to indicate in MDL for compound values, such as user-defined structure type values, how they correspond to ports on a graph node:
	• The value `node_port_value_only` defines that a compound value corresponds to a single port named out.
	• The value `node_port_fields_only` defines that each field of the compound value corresponds to its own port.
	• The value `node_port_value_and_fields` defines that both kind of ports are available at the same time.
	Note: In addition, individual fields can be hidden with the standard `hidden` annotation.

`node_output_port_default(`
    `node_port_mode mode`
        `= node_port_value_only)`
	Specifies the default configuration of output ports for a newly created node corresponding to an MDL function. It is applicable on the return type of MDL functions or on definitions of user-defined structure types. The annotation on a function return type takes precedence over the annotation on a structure type when both are present.
	
	Note: This annotation is used to mediate how the single output of MDL functions through its return value works with external node systems with multiple outputs, see also Section 28.1 in the Appendix.

`native()`	Specifies a hint to an integration that the annotated function or material might have a native implementation. Integrations can use this annotation to distinguish between definitions that need to be passed to the parts in the integration that handle native implementations or that can be inlined and optimized early on. Note that using the implementation from the MDL definition must always be a valid choice and shall result in the intended behavior. Native implementations can typically be used for performance optimizations otherwise unavailable.
`noinline()`	Specifies a hint that the annotated function or material should not be inlined by the compiler. Integrations may aggressively inline functions for performance. This annotation can guide integrations where to refrain from inlining.

19   Renderer state

Materials and functions need access to some common values available in the renderer, such as some varying aspect of the current fragment being shaded or a uniform property of the render pass. MDL gives access to these values through a set of global functions, the *renderer state functions*, or *state functions* for short.

Note: The renderer state is thus immutable and cannot be changed in a function or material. However, some material properties influence the renderer state of later stages, see Section 13 for details.

Although the renderer state cannot be defined in MDL itself, it is made available through one of the standard MDL modules, see Section 16. The `state` module can be imported as any other module, for example with:

```
import ::state::*;
```

All the regular scoping and shadowing rules apply. For example, this allows to access the `normal` state function using its fully qualified name in case it has been shadowed as in the following example:

```
material normal_parameter_example( float3 normal = state::normal())
    = material( ...);
```

MDL materials and functions are used in the renderer in different contexts, for example, when rendering a surface or when rendering a volume. Not all state functions are well defined in all contexts. Yet, in order to enable generic functions, for example, for texture lookups on surfaces as well as for environments, all state functions are always defined and return sensible defaults in such occasions. The defaults are documented in detail below.

Most state functions are varying and only a few are uniform such as `transform(...)`. All state functions are documented with their explicit uniform or varying property below.

19.1   Basic renderer state values

The following is a list of all basic renderer state values. Note that all spatial values are in internal space, see 19.2 for coordinate space transformation functions.

`float3 position() varying`	The intersection point on the surface or the sample point in the volume. The default value is zero for contexts without a position, such as the environment.
`float3 normal() varying`	The shading surface normal as a unit-length vector. The value is a unit-length vector facing to the origin if the context is the environment. The default value is zero for contexts without a normal, which are volumes and hair shading. For regular surface shading contexts, the normal is facing outward from the volume. Since thin-walled materials are treated as enclosing an infinitesimally thin volume, both sides are outward and the normal always points to the observer.
`float3 geometry_normal() varying`	The true geometric surface normal for the current geometry as a unit-length vector. The value is a unit-length vector facing to the origin if the context is the environment. The default value is zero for contexts without a normal, which are volumes and hair shading.
`float3 motion() varying`	Tangential motion vector.
`int texture_space_max() varying`	The maximal number of texture spaces available.

`float3 texture_coordinate(`
`    int index`
`) varying`
	The texture space at the given index where $0 \leq$ index $<$ texture_space_max(). Returns the zero vector if the index is outside of this range.
	
	In volume shading, accessing texture spaces and their respective tangents return the coordinates and tangents at the surface entry point of the current light-transport path. Note that using these may lead to inconsistencies in bidirectional techniques.
	
	In hair shading, texture spaces contain the following values:
	
	    `texture_coordinate(0).x`: The normalized position of the intersection point along the hair fiber in the range from zero for the root of the fiber to one for the tip of the fiber. `texture_coordinate(0).y`: The normalized position of the intersection point around the hair fiber in the range from zero to one. `texture_coordinate(0).z`: The thickness of the hair fiber at the intersection point in internal space. `texture_coordinate(1)`: A position of the root of the hair fiber, for example, from a texture space of a surface supporting the hair fibers. This position is constant for a fiber.

`float3 texture_tangent_u(`
`    int index`
`) varying`
	The array of tangent vectors for each texture space. The tangent vector is a unit length vector in the plane defined by the surface normal, which points in the direction of the projection of the tangent to the positive u axis of the corresponding texture space onto the plane defined by the original surface normal. Not provided in hair shading and set to zero in this case. Returns the zero vector if the index is smaller than zero or larger or equal than `texture_space_max()`.

`float3 texture_tangent_v(`
`    int index`
`) varying`
	The array of bitangent vectors for each texture space. The bitangent vector is a unit length vector in the plane defined by the surface normal, which points in the general direction of the positive v axis of the corresponding texture space, but is orthogonal to both the original surface normal and the tangent of the corresponding texture space. Not provided in hair shading and set to zero in this case. Returns the zero vector if the index is smaller than zero or larger or equal than `texture_space_max()`.

`float3x3 tangent_space(`
`    int index`
`) varying`
	The array of tangent space matrices for each texture space. These matrices are available as a convenience and are constructed from the `texture_tangent_u`, `texture_tangent_v`, and surface normal as the x, y, and z axis of the coordinate system, respectively. Not provided in hair shading and set to zero in this case.

`float3 geometry_tangent_u(`
`    int index`
`) varying`
	Array of geometry tangents. Together with `geometry_normal` and `geometry_tangent_v`, this forms a number of orthonormal bases. The orientation of each basis around the normal is the same as that of `tangent_space`. Not provided in hair shading and set to zero in this case. Returns the zero vector if the index is smaller than zero or larger or equal than `texture_space_max()`.

`float3 geometry_tangent_v(`
`    int index`
`) varying`
	Array of geometry bitangents. Together with `geometry_normal` and `geometry_tangent_u`, this forms a number of orthonormal bases. Not provided in hair shading and set to zero in this case. Returns the zero vector if the index is smaller than zero or larger or equal than `texture_space_max()`.

`int object_id() uniform`	Returns the object ID provided in a scene, and zero if none was given or for the environment.
`float3 direction() varying`	Lookup direction in the context of an environment lookup and `float3(0.0)` in all other contexts.
`float animation_time() varying`	The time of the current sample in seconds, including the time within a shutter interval.
`const int WAVELENGTH_BASE_MAX`	The number of wavelengths returned in the result of `wavelength_base()`.
`float[WAVELENGTH_BASE_MAX]` `wavelength_base() uniform`	Array of wavelengths, in increasing order, that are recommended when constructing spectra to achieve best approximation results (see Section 6.13.1). Wavelengths are given in nanometers [nm]. Each wavelength λ is between the shortest and longest wavelengths considered for spectra, defined by `limits::WAVELENGTH_MIN` $\leq \lambda \leq$ `limits::WAVELENGTH_MAX`.
`float wavelength_min() uniform`	The smallest `float` value that the current platform allows for representing wavelengths for the `color` type and its related functions.
`float wavelength_max() uniform`	The largest `float` value that the current platform allows for representing wavelengths for the `color` type and its related functions.

19.2   Coordinate space transformations

The state provides functions to transform spatial values—namely scales, vectors, points and normals—between the following coordinate spaces:

- internal space
- object space
- world space

Spatial values returned by state functions are always provided in internal space unless noted otherwise. Internal space is implementation dependent and can vary across different platforms. If a material or function can perform calculations independently of the coordinate system then it can operate with those values directly, otherwise it will need to transform them into a known space.

`enum coordinate_space {`
`    coordinate_internal,`
`    coordinate_object,`
`    coordinate_world`
`};`
	The coordinate space determines in which space coordinates and other spatial values are represented and in which space their representation is transformed into.

`float4x4 transform(`
    `coordinate_space from,`
    `coordinate_space to`
`) uniform`
	Returns a transformation matrix to transform from one space to another. The `from` and `to` parameters can be any of the `coordinate_space` enumeration values.
	
	The matrix returned from `transform()` assumes that vectors are considered to be column vectors and multiplied on the right-hand side of the matrix. In other words, the translation components T_x, T_y, and T_z of a translation-only transformation are located in the following positions of the returned matrix:
	
	$$\begin{pmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$
	
	See also Section 6.11 for the other relevant conventions on matrices.

`float3 transform_point(`
    `coordinate_space from,`
    `coordinate_space to,`
    `float3 point`
`) uniform`
	Transforms a point from one coordinate system to another. The `from` and `to` parameters can be any of the `coordinate_space` enumeration values.

`float3 transform_vector(`
    `coordinate_space from,`
    `coordinate_space to,`
    `float3 vector`
`) uniform`
	Transforms a vector from one coordinate system to another. The translation component of the coordinate systems is ignored when transforming the vector. The `from` and `to` parameters can be any of the `coordinate_space` enumeration values.

`float3 transform_normal(`
    `coordinate_space from,`
    `coordinate_space to,`
    `float3 normal`
`) uniform`
	Transform a surface normal from one coordinate system to another. As with vector transformations, the translation component of the coordinate systems is ignored. Additionally the transpose of the inverse transformation matrix is used to properly transform the surface normal. The `from` and `to` parameters can be any of the `coordinate_space` enumeration values.

`float transform_scale(`
    `coordinate_space from,`
    `coordinate_space to,`
    `float scale`
`) uniform`
	Transforms a scale measure from one coordinate system to another. Only the uniform scale factor of the coordinate system transformation is used. If the transformation is not a similarity transform, the average of the non-uniform scale factors is used. The `from` and `to` parameters can be any of the `coordinate_space` enumeration values.

Note that for all transform functions, if the `from` argument is `coordinate_internal` then the coordinates to transform should be a return value of a state function or a value that has been previously transformed into internal space. Otherwise, the result is undefined and may differ across implementations.

For example the result of:

```
transform_point( coordinate_internal,
                 coordinate_world,
                 float3(1,0,0))      // ! undefined behavior
```

is undefined since the definition of the coordinates (1,0,0) in internal space is implementation dependent.

The world space is in *scene units*, which can vary from integration to integration and scene to scene. The following state functions offer conversion factors between scene units and meters:

`float meters_per_scene_unit() uniform`	Returns the distance of one scene unit in meters.
`float scene_units_per_meter() uniform`	Returns the distance of one meter in scene units.

19.3   Rounded corners state function

```float3 rounded_corner_normal(uniform float radius = 0.0, uniform bool across_materials = false, uniform float roundness = 1.0) varying```	Returns a modified shading normal `state::normal` that is changed near surface mesh edges to blend smoothly into the shading normal of neighboring facets. The result of this function can be used to set the `normal` field of the `material_geometry` structure, which results in a perceived look of smooth edges instead of a facetted look with hard edges. It can as well be combined with normal perturbation schemes.
	`radius` – influence radius around the edges within which the normal is modified. The radius is specified in meters in world space. A radius of 0.0 disables the rounded corners and this function just returns `state::normal`.
	`across_materials` – normal smoothing happens only between facets of equal material, unless this parameter is set `true`, in which case the smoothing happens between facets irrespective of their materials.
	`roundness` – determines how round the edge will look. The valid range is between 0.0 and 1.0. A value of 0.0 chamfers the edge and a value of 1.0 gives a rounded edge.

20 Standard library functions

MDL defines a standard library of built-in functions and a few constants. Many of these functions are overloaded to support different MDL scalar and vector data types. A list of overloaded versions of each standard library function is included with each description. The following generic types are used in these function signatures to abbreviate common overloads of vector types and floating-point types.

Generic type	Represents one of these types
boolN	`bool`, `bool2`, `bool3`, `bool4`
intN	`int`, `int2`, `int3`, `int4`
float	`float`, `double`
floatN	`float`, `float2`, `float3`, `float4`, `double`, `double2`, `double3`, `double4`

For any specific function signature, if more than one generic type is used to represent a vector type, all of those vector types need to have the same number of fields, and if more than one generic type is used to represent a floating-point type, all of those types need to be of single precision or double precision.

The vector versions of the standard library functions operate component-wise unless noted otherwise. The description is per component.

The standard library functions and constants are made available through the standard MDL modules, see Section 16 and the individual sections below. For example, the `math` module can be imported as any other module:

```
import ::math::*;
```

All the regular scoping and shadowing rules apply. For example, this allows to access the `abs` standard math function using its fully qualified name in case it has been in shadowed as in the following example:

```
float stdlib_shadowing_example( float max) {
    return math::max( 1.0, max);
}
```

20.1 Math constants

The following standard math constants are made available through the standard `math` module (Section 16):

```
import ::math::*;
```

`const float PI`	`= 3.14159265358979323846f`
`const float TWO_PI`	`= 6.28318530717958647692f`
`const float HALF_PI`	`= 1.57079632679489661923f`

20.2 Math functions

The following standard math functions, including some geometric and color related functions, are made available through the standard `math` module (Section 16):

```
import ::math::*;
```

All standard math functions are uniform and not documented as such explicitly below.

intN `abs( `*intN*` a)`	Returns the absolute value.
floatN `abs( `*floatN*` a)`	
`color abs( color a)`	

floatN `acos( `*floatN*` a)`	Returns the arc cosine.
`bool  all( `*boolN*` a)`	Returns `true` if all components are `true` and `false` otherwise.
`bool  any( `*boolN*` a)`	Returns `true` if any component is `true` and `false` otherwise.
floatN `asin( `*floatN*` a)`	Returns the arc sine.
floatN `atan( `*floatN*` a)`	Returns the arc tangent.
floatN `atan2( `*floatN*` y, `*floatN*` x)`	Returns the arc tangent of `y/x`. The signs of `y` and `x` are used to determine the quadrant of the result.
float `  average( `*floatN*` a)` `float average( color a)`	Returns the average of the vector elements or the color.
`color blackbody(` `    float temperature)`	Returns the color for a blackbody radiator at the given temperature in Kelvin.
floatN `ceil( `*floatN*` a)`	Returns the nearest integer that is greater than or equal to the value.

intN` clamp( `*intN*`   a, `*intN*`   min, `*intN*`   max)`
intN` clamp( `*intN*`   a, int   min, `*intN*`   max)`
intN` clamp( `*intN*`   a, `*intN*`   min, int   max)`
intN` clamp( `*intN*`   a, int   min, int   max)`
floatN` clamp( `*floatN*` a, `*floatN*` min, `*floatN*` max)`
floatN` clamp( `*floatN*` a, `*float*`   min, `*floatN*` max)`
floatN` clamp( `*floatN*` a, `*floatN*` min, `*float*`   max)`
floatN` clamp( `*floatN*` a, `*float*`   min, `*float*`   max)`
`color clamp( color a, color min, color max)`
`color clamp( color a, float min, color max)`
`color clamp( color a, color min, float max)`
`color clamp( color a, float min, float max)`
	Returns `min` if a is less than `min`, `max` if a is greater than `max`, and a otherwise.

floatN `cos( `*floatN*` a)`	Returns the cosine. Angles specified by `a` are in radians.
floatN `cosh( `*floatN*` a)`	Returns the hyperbolic cosine. Angles specified by `a` are in radians.

`float3 cross(`
`    `*float*`3 a,`
`    `*float*`3 b)`
	Returns the cross product of `a` and `b`.

floatN `degrees( `*floatN*` a)`	Converts the value from radians to degrees, i.e, returns $180 \cdot \text{a}/\pi$.
float `  distance( `*floatN*` a, `*floatN*` b)`	Returns the Euclidean distance between `a` and `b`.
float `  dot( `*floatN*` a, `*floatN*` b)`	Returns the dot product of `a` and `b`.

`color emission_color(`
`    color value)`
`color emission_color(`
`    float[<N>] wavelengths,`
`    float[N] amplitudes)`
	The first variant re-interprets a unitless reflectivity in its color `value` as an emission intensity. The second variant returns the color best representing the light emission intensity defined by the two `float` arrays that define samples for a smooth spectrum representation. The first array contains the wavelengths in increasing order and the second array, which must be of equal size, contains the amplitude values at these wavelengths. The construction may choose an approximation to represent the spectrum.

`float eval_at_wavelength(`
    `color a,`
    `float wavelength)`
	Evaluates and returns the value of a at the given wavelength, where the wavelength argument is given in nanometers [nm] and `limits::WAVELENGTH_MIN` $\leq$ `wavelength` $\leq$ `limits::WAVELENGTH_MAX`.

floatN `exp(` *floatN* `a)` `color exp( color a)`	Returns the constant e raised to the power a.
floatN `exp2(` *floatN* `a)` `color exp2( color a)`	Returns the value two raised to the power a.
`int float_bits_to_int( float a)`	Returns the signed-integer value representing the encoding of the floating-point value a.
floatN `floor(` *floatN* `a)`	Returns the nearest integer that is less than or equal to the value.
floatN `fmod(` *floatN* `a,` *floatN* `b)` *floatN* `fmod(` *floatN* `a, float b)`	Returns a modulo b, in other words, the remainder of a/b. The result has the same sign as a.
floatN `frac(` *floatN* `a)`	Returns the positive fractional part.
`float int_bits_to_float( int a)`	Returns the floating-point value corresponding to the signed-integer encoding a of a floating-point value. If an inf or NaN is passed in, it will not signal, and the resulting floating-point value is unspecified. Otherwise, the bit-level representation is preserved.
boolN `isnan(` *floatN* `a)`	Returns `true` if the value does not represent a valid number and `false` otherwise. This can occur as the result of an invalid operation such as taking the square root of a negative number.
boolN `isfinite(` *floatN* `a)`	Returns `true` if the value represents a valid and finite number, and `false` otherwise.
float `length(` *floatN* `a)`	Returns the length of a.

floatN `lerp(` *floatN* `a,` *floatN* `b,` *floatN* `l)`
floatN `lerp(` *floatN* `a,` *floatN* `b, float l)`
`color lerp( color a, color b, color l)`
`color lerp( color a, color b, float l)`
	Returns the linear interpolation between a and b based on the value of l, such that the result is $a \cdot (1 - l) + b \cdot l$.

floatN `log(` *floatN* `a)` `color log( color x)`	Computes the natural logarithm.
floatN `log2(` *floatN* `a)` `color log2( color x)`	Computes the base two logarithm.
`float luminance( float3 a)` `float luminance( color a)`	Returns the Y channel (luminance) of a when interpreting a in the CIE XYZ color space. The color space of a is implementation dependent if a is of type `color` and assumes the linear sRGB color space if a is of type `float3`. In the latter case, the luminance is then equal to $0.212671 \cdot \texttt{a.x} + 0.715160 \cdot \texttt{a.y} + 0.072169 \cdot \texttt{a.z}$.

intN max(*intN* a, *intN* b) *intN* max(int a, *intN* b) *intN* max(*intN* a, int b) *floatN* max(*floatN* a, *floatN* b) *floatN* max(*float* a, *floatN* b) *floatN* max(*floatN* a, *float* b) color max(color a, color b) color max(*float* a, color b) color max(color a, *float* b)	Returns the maximum of a and b.
float max_value(*floatN* a) float max_value(color a)	Returns the largest value of a.
float max_value_wavelength(color a)	Returns the smallest wavelength in [nm] at which the largest value lies.
intN min(*intN* a, *intN* b) *intN* min(int a, *intN* b) *intN* min(*intN* a, int b) *floatN* min(*floatN* a, *floatN* b) *floatN* min(*float* a, *floatN* b) *floatN* min(*floatN* a, *float* b) color min(color a, color b) color min(*float* a, color b) color min(color a, *float* b)	Returns the minimum of a and b.
float min_value(*floatN* a) float min_value(color a)	Returns the smallest value of a.
float min_value_wavelength(color a)	Returns the smallest wavelength in [nm] at which the smallest value lies.
floatN[2] modf(*floatN* a)	Returns an array with the integral part of a as first element and the fractional part of a as second element. Both the fractional and integer parts have the same sign as a.
floatN normalize(*floatN* a)	Scales a by the reciprocal of its length to give it a length of 1. If the length of a is zero the result of normalize(a) is undefined.
intN pow(*intN* a, *intN* b) *intN* pow(*intN* a, int b) *floatN* pow(*floatN* a, *floatN* b) *floatN* pow(*floatN* a, *float* b) color pow(color a, color b) color pow(color a, float b)	Returns a raised to the power b. Floating-point value a must not be negative, while for the overloaded functions with integer exponent b, the integer value a may be negative.
floatN radians(*floatN* a)	Converts the value from degrees to radians, i.e, returns $\pi \cdot a / 180$.
floatN round(*floatN* a)	Returns the nearest integer value for a.
floatN rsqrt(*floatN* a) color rsqrt(color a)	Returns the reciprocal of the square root of a.
floatN saturate(*floatN* a) color saturate(color a)	Clamps a so that $0.0 \le a \le 1.0$.

intN sign(*intN* a) *floatN* sign(*floatN* a)	Returns 1 if a is greater than 0, -1 if a is less than 0, and 0 otherwise.
floatN sin(*floatN* a)	Returns the sine of a. Angles specified by a are in radians.
floatN[2] sincos(*floatN* a)	Returns an array with the sine of a as first element and the cosine of a as second element. Angles specified by a are in radians.
floatN sinh(*floatN* a)	Returns the hyperbolic sine. Angles specified by a are in radians.
floatN smoothstep(*floatN* a, *floatN* b, *floatN* l) *floatN* smoothstep(*floatN* a, *floatN* b, *float* l)	Returns 0 if l is less than a and 1 if l is greater than b. A smooth Hermite-interpolation curve is applied in-between so that the return value varies continuously from 0 to 1 as l varies from a to b; it returns $t^2(3 - 2t)$ where $t = (\text{clamp}(l, a, b) - a)/(b - a)$. The return value is undefined if a is greater than or equal to b.
floatN sqrt(*floatN* a) color sqrt(color a)	Returns the square root of a
floatN step(*floatN* a, *floatN* b)	Returns 0 if b is less than a and 1 otherwise.
floatN tan(*floatN* a)	Returns the tangent of a. Angles specified by a are in radians.
floatN tanh(*floatN* a)	Returns the hyperbolic tangent of a. Angles specified by a are in radians.
float2x2 transpose(float2x2 a) float2x3 transpose(float3x2 a) float3x2 transpose(float2x3 a) float3x3 transpose(float3x3 a) float4x2 transpose(float2x4 a) float2x4 transpose(float4x2 a) float3x4 transpose(float4x3 a) float4x3 transpose(float3x4 a) float4x4 transpose(float4x4 a) double2x2 transpose(double2x2 a) double2x3 transpose(double3x2 a) double3x2 transpose(double2x3 a) double3x3 transpose(double3x3 a) double4x2 transpose(double2x4 a) double2x4 transpose(double4x2 a) double3x4 transpose(double4x3 a) double4x3 transpose(double3x4 a) double4x4 transpose(double4x4 a)	Computes the transpose of the matrix a.

20.3   Texture functions

The following standard texture functions are made available through the standard `tex` module (Section 16):

```
import ::tex::*;
```

The uniform or varying modifier for the standard texture functions is documented explicitly.

```int width(uniform texture_2d tex, int2 uv_tile = int2(0,0), float frame = 0.0) uniform```	The width of the texture `tex` at the given *uv* tile in texels along the u-direction in texel space. The width is zero for an invalid texture reference or if the *uv*-tile does not exist.
```int width(uniform texture_3d tex, float frame = 0.0) uniform int width(uniform texture_cube tex) uniform```	The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence.
```int height(uniform texture_2d tex, int2 uv_tile = int2(0,0), float frame = 0.0) uniform```	The height of the texture `tex` at the given *uv* tile in texels along the v-direction in texel space. The height is zero for an invalid texture reference or if the *uv*-tile does not exist.
```int height(uniform texture_3d tex, float frame = 0.0) uniform int height(uniform texture_cube tex) uniform```	The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence.
```int depth(uniform texture_3d tex, float frame = 0.0) uniform```	The depth of the texture `tex` in texels along the w-direction in texel space. The depth is zero for an invalid texture reference.

The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence. |
| ```int width_offset(uniform texture_3d tex,   float frame = 0.0) uniform``` | The *x*-coordinate of the left-bottom-back corner of the volume bounding box in texels in texel space, which corresponds to the grid space for OpenVDB. The value is zero for an invalid texture reference.

The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence. |
| ```int height_offset(uniform texture_3d tex,   float frame = 0.0) uniform``` | The *y*-coordinate of the left-bottom-back corner of the volume bounding box in texels in texel space, which corresponds to the grid space for OpenVDB. The value is zero for an invalid texture reference.

The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence. |
| ```int depth_offset(uniform texture_3d tex,   float frame = 0.0) uniform``` | The *z*-coordinate of the left-bottom-back corner of the volume bounding box in texels in texel space, which corresponds to the grid space for OpenVDB. The value is zero for an invalid texture reference.

The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence. |

```int first_frame(` ` uniform texture_2d tex` `) uniform` `int first_frame(` ` uniform texture_3d tex` `) uniform```	Returns the first frame number of the texture sequence `tex`, and zero if `tex` is not a texture sequence.
```int last_frame(` ` uniform texture_2d tex` `) uniform` `int last_frame(` ` uniform texture_3d tex` `) uniform```	Returns the last frame number of the texture sequence `tex`, and zero if `tex` is not a texture sequence.
```float4x4 grid_to_object_space(` ` uniform texture_3d tex,` ` float frame = 0.0` `) uniform```	Returns the transform matrix from the `texture_3d` texel space to the object space. If the texture is in the OpenVDB file format, texel space corresponds with the OpenVDB grid space and object space corresponds with the OpenVDB world space. Note: This matrix might not be an orthonormal matrix. It can contain shear or perspective transforms. To obtain an MDL object space representation of an OpenVDB grid space bounding box, above texel space functions can be used to construct all eight corners in grid space and transform them to MDL object space. The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence.
```bool texture_isvalid(uniform texture_2d tex) uniform` `bool texture_isvalid(uniform texture_3d tex) uniform` `bool texture_isvalid(uniform texture_cube tex) uniform` `bool texture_isvalid(uniform texture_ptex tex) uniform```	Returns `true` if the value of `tex` is a valid texture reference and `false` otherwise.

The standard texture lookup functions are provided in different variants, which differ only in the lookup type *ltype*, which is used as part of the function name and which determines the return type of the lookup function. The generic lookup type *ltype* can be any of the following types:

Generic type	Represents one of these types
ltype	`float`, `float2`, `float3`, `float4`, `color`

The standard texture lookup function for the `texture_ptex` is varying and the other standard texture functions are uniform. Note that their result is usually varying because of the use of a varying state value for their lookup coordinate parameter. All functions are documented accordingly with their explicit uniform or varying property below.

```
enum gamma_mode {
    gamma_default,
    gamma_linear,
    gamma_srgb
};
```

The gamma mode determines whether a texture can be used as is in the linear workflow of the renderer or if it needs to be inverse-gamma corrected. The value `gamma_default` leaves this decision up to the texture itself. The value `gamma_linear` defines that the texture can be used as is. The value `gamma_srgb` defines that the texture uses the gamma compression of the sRGB standard, which is close to a gamma factor of 2.2, and the texture needs to be inverse-gamma corrected by the integration before use.

Note: This mode is only used in the texture constructors that create a texture from a file path as defined in Section 6.14.1.

```
enum wrap_mode {
    wrap_clamp,
    wrap_repeat,
    wrap_mirrored_repeat,
    wrap_clip
};
```

The wrap mode determines the texture lookup behavior if a lookup coordinate is exceeding the normalized half-open texture space range of $[0, 1)$: `wrap_clamp` clamps the lookup coordinate to the range, `wrap_repeat` takes the fractional part of the lookup coordinate effectively repeating the texture along this coordinate axis, `wrap_mirrored_repeat` is like `wrap_repeat` but takes one minus the fractional part every other interval to mirror every second instance of the texture, and `wrap_clip` makes the texture lookup return zero for texture coordinates outside of the range.

```
ltype lookup_ltype(
    uniform texture_2d tex,
    float2 coord,
    uniform wrap_mode wrap_u = wrap_repeat,
    uniform wrap_mode wrap_v = wrap_repeat,
    uniform float2 crop_u = float2(0.0, 1.0),
    uniform float2 crop_v = float2(0.0, 1.0),
    float frame = 0.0
) uniform
```

Returns the sampled texture value for the two-dimensional coordinates `coord` given in normalized texture space in the range $[0, 1)^2$, where the wrap modes define the behavior for coordinates outside of that range. The crop parameters further define a sub-range on the texture that is actually used and that defines the normalized texture space in the range $[0, 1)^2$. The crop parameter defaults `float2(0.0, 1.0)` corresponds to the whole texture in the corresponding axis.

The wrap mode and crop parameters are ignored if the texture references a uv-tileset. In this case, `floor(coord)` defines the index to select the tile in the uv-tileset and `coord-floor(coord)` defines the *uv* coordinates to look up the sampled texture value in the normalized texture space in the range $[0, 1)^2$ for the selected tile.

The `frame` parameter selects the texture frame if `tex` refers to a texture sequence. The lookup may use interpolation in case `frame` is not integral.

A lookup on an invalid texture reference or a non-existing *uv*-tile or texture sequence frame returns zero.

---

ltype `lookup_`*ltype*`(`
    `uniform texture_3d tex,`
    `float3 coord,`
    `uniform wrap_mode wrap_u = wrap_repeat,`
    `uniform wrap_mode wrap_v = wrap_repeat,`
    `uniform wrap_mode wrap_w = wrap_repeat,`
    `uniform float2 crop_u = float2(0.0, 1.0),`
    `uniform float2 crop_v = float2(0.0, 1.0),`
    `uniform float2 crop_w = float2(0.0, 1.0),`
    `float frame = 0.0`
`) uniform`

Returns the sampled texture value for the three-dimensional coordinates `coord` given in normalized texture space in the range $[0,1)^3$, where the wrap modes define the behavior for coordinates outside of that range. The crop parameters further define a sub-range on the texture that is actually used and that defines the normalized texture space in the range $[0,1)^3$. The crop parameter defaults `float2(0.0, 1.0)` corresponds to the whole texture in the corresponding axis.

If the texture references an OpenVDB file, the wrap mode and crop parameters are ignored, and `coord` is defined in object space for the lookup in the OpenVDB grid. In this case, OpenVDB world space corresponds with the MDL object space.

The `frame` parameter selects the texture frame if `tex` refers to a texture sequence. The lookup may use interpolation in case `frame` is not integral.

A lookup on an invalid texture reference or non-existing texture sequence frame returns zero.

---

ltype `lookup_`*ltype*`(`
    `uniform texture_cube tex`
    `float3 coord`
`) uniform`

Returns the sampled texture value for a cube texture lookup in the direction given by the three-dimensional vector `coord`. A lookup on an invalid texture reference returns zero.

---

ltype `lookup_`*ltype*`(`
    `uniform texture_ptex tex,`
    `int channel = 0`
`) varying`

Returns the sampled PTEX texture value for the current surface position starting at the channel provided with the `channel` parameter. A lookup on an invalid texture reference or beyond available channels returns zero.

---

ltype `texel_`*ltype*`(`
    `uniform texture_2d tex,`
    `int2 coord,`
    `int2 uv_tile = int2(0,0),`
    `float frame = 0.0`
`) uniform`

Returns the raw texture value for the two-dimensional coordinates `coord` in the valid range $[0, \mathtt{width(tex,uv\_tile)} - 1] \times [0, \mathtt{height(tex,uv\_tile)} - 1]$.

The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence.

A lookup on an invalid texture reference, a non-existing *uv*-tile, a non-existing texture sequence frame, or outside the valid range returns zero.

---

ltype `texel_`*ltype*`(`
`    uniform texture_3d tex,`
`    int3 coord`
`    float frame = 0.0`
`) uniform`
	Returns the raw texture value for the three-dimensional coordinates `coord` in the valid range $[0,$ `width(tex)` $-1] \times [0,$ `height(tex)` $-1] \times [0,$ `depth(tex)` $-1]$.
	
	The integral part of `frame` selects the texture frame if `tex` refers to a texture sequence.
	
	A lookup on an invalid texture reference or outside the valid range or texture sequence frame returns zero.

20.4   Scene data

The following standard scene data functions are made available through the standard `scene` module (Section 16):

```
import ::scene::*;
```

Scene data can be associated with geometry or with global attributes in the scene. Scene data on geometry shall take precedence over equally named global scene attributes. Scene data on geometry can have different interpolation modes, of which some will result in uniform data, while the others result in varying data. MDL does not specify where scene data needs to be stored or its interpolation mode.

The uniform or varying modifier for the standard scene data functions is documented explicitly.

`bool data_isvalid( uniform string name) uniform`	Returns `true` if the argument provided to the `name` parameter references an existing scene data value and `false` otherwise. Type and interpolation mode of the scene data is ignored.

The standard scene data lookup functions are provided in different variants, which differ only in the lookup type *ltype* and type modifier `uniform`, which are used as part of the function name and which determine the return type of the lookup function. The generic lookup type *ltype* can be any of the following types:

Generic type	Represents one of these types
ltype	`int, int2, int3, int4, float, float2, float3, float4, float4x4, color`

The scene data can have a different type as the requested lookup type in the lookup function. Integrations shall convert the scene data value to the lookup type in a semantically plausible way based on the supported scene data types.

The standard scene data lookup functions exists in two versions, one for varying data and one for uniform data.

ltype `data_lookup_`*ltype*`(`
`    uniform string name,`
    ltype`          default_value = `*ltype*`()`
`) varying`
	Returns the scene data of the give name at the current shade point (for geometry scene data) or the global scene data.
	
	A lookup on an unknown scene data name or one with incompatible type returns the default_value.

`uniform` *ltype* `data_lookup_uniform_`*ltype*`(`
    `uniform string name,`
    `uniform` *ltype*   `default_value = `*ltype*`()`
`) uniform`
	Returns the scene data of the give name at the current shade point (for geometry scene data) or the global scene data.
	
	A lookup on an unknown scene data name or one with incompatible type or varying type returns the `default_value`.

20.5   Debugging functions

The following standard debugging functions are made available through the standard `debug` module (Section 16):

        import ::debug::*;

All standard debug functions are uniform and not documented as such explicitly below. These functions have no observable effect for the MDL program except the possible end of the program execution. A system can ignore these functions and replace them with the value `true`.

`bool print(` *boolN* `a)`
`bool print(` *intN*   `a)`
`bool print(` *floatN* `a)`
`bool print( color a)`
`bool print( string a)`
	Prints the value of a. Returns `true`.

`bool assert(`
    `bool condition,`
    `string reason`
`)`
	Aborts program execution if `condition` is false and prints the reason text. Returns `true` otherwise.

`bool breakpoint()`	Establishes a breakpoint at this position for a debugger. Returns `true`.

21 Standard distribution functions

MDL defines a standard set of elemental distribution functions, modifiers, and combiners that are used in defining materials in Section 13. The distribution functions define light interaction at a boundary (reflection and transmission), light scattering in participating media, and the emission of light from a surface.

The distributions, modifiers, and combiners are made available in MDL programs by loading the `df` module, in the same manner as the modules described in Section 15:

```
import ::df::*;
```

The regular scoping and shadowing rules apply to all symbols imported from the `df` module. However, unlike the other modules, the `df` module is not written in MDL; it requires a tight coupling with the rendering system that is outside the scope of MDL itself.

21.1 Bidirectional scattering distribution functions

This section documents the elemental *bidirectional scattering distribution function* (BSDF) models defined in MDL and their input parameters. Defining an instance of these BSDF models uses the syntax of a function returning a `bsdf`, which is not allowed elsewhere in MDL.

Inputs have to meet some requirements to ensure energy conservation. Unless noted otherwise, the main criterion is for color inputs to be in $[0, 1]$. In some cases models have to enforce additional restrictions. Two principal approaches are possible when normalizing color inputs. First, colors may be clamped, that is, values outside of $[0, 1]$ are set to the boundary values. Second, colors may be divided by their maximum value if it is larger than one. The former approach is slightly faster, while the latter avoids color shifts.

Several BSDFs, such as `specular_bsdf` and `simple_glossy_bsdf`, require the definition of their *scattering mode*, represented by an enum parameter of the BSDF:

```
enum scatter_mode {
    scatter_reflect,
    scatter_transmit,
    scatter_reflect_transmit
};
```
Specular modes for reflection, transmission, or both.

21.1.1 Diffuse interaction

```
bsdf diffuse_reflection_bsdf (
  color         tint     = color(1.0),
  float         roughness = 0.0,
  uniform string handle    = ""
);
```

Lambertian reflection extended by the Oren-Nayar microfacet model [5].

   tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

roughness – Oren-Nayar roughness coefficient, simulating view-dependent diffuse reflection. Range: $[0, 1]$, with 0 specifying complete view independence.

  handle – Name to provide access to this component for use in an MDL integration.

```
bsdf diffuse_transmission_bsdf(
  color          tint   = color(1.0),
  uniform string handle = ""
);
```

Pure diffuse transmission of light through a surface.

  tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

  handle – Name to provide access to this component for use in an MDL integration.

```
bsdf dusty_diffuse_reflection_bsdf (
  color          tint   = color(1.0),
  uniform string handle = ""
);
```

Diffuse reflection modeling spherical Lambertian scatterers [6].

  tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

  handle – Name to provide access to this component for use in an MDL integration.

21.1.2   Specular interaction

Specular reflections and transmissions implement an idealized surface in which light is reflected in the mirror direction or is transmitted based on the index of refraction of the boundary using Snell's law.

```
bsdf specular_bsdf(
  color               tint   = color(1.0),
  uniform scatter_mode mode   = scatter_reflect,
  uniform string       handle = ""
);
```

Pure specular reflection and/or transmission. Uses the reflection color in transmission mode if the ior values indicate total interior reflection.

  tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

  mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

  handle – Name to provide access to this component for use in an MDL integration.

21.1.3   Glossy interaction

Glossy reflections can be anisotropic and are therefore dependent upon the orientation of the surface specified by its local coordinate system. The following two BSDFs can override this coordinate system by specifying the tangent in the *u* direction.

Higher roughness values in glossy microfacet models lower the albedo due to missing multiscatter contributions. Energy conservation is achieved by adding a weighted diffuse component[10], which is available with an additional `multiscatter_tint` parameter for the `scatter_reflect` and scat-

ter_reflect_transmit scatter modes, but not for the scatter_transmit one.

```
bsdf simple_glossy_bsdf(
  float                roughness_u,
  float                roughness_v      = roughness_u,
  color                tint             = color(1.0),
  color                multiscatter_tint = color(0.0),
  float3               tangent_u        = state::texture_tangent_u(0),
  uniform scatter_mode mode             = scatter_reflect,
  uniform string       handle           = ""
);
```

Glossy reflection and transmission based on a microfacet model [7] using a Phong distribution [8] and a v-cavities shadowing term [9]. The Phong distribution exponent is computed as $exponent = 2/roughness^2$. Becomes black in transmission mode if the ior values indicate total interior reflection.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

handle – Name to provide access to this component for use in an MDL integration.

```
bsdf backscattering_glossy_reflection_bsdf(
   float          roughness_u,
   float          roughness_v       = roughness_u,
   color          tint              = color(1.0),
   color          multiscatter_tint = color(0.0),
   float3         tangent_u         = state::texture_tangent_u(0),
   uniform string handle            = ""
);
```

reflection based on the retro-reflective component of the halfway-vector disk model using the scaling projection [12]. Since that BRDF is not symmetric, two modifications are applied. First, instead of a disk distribution $p(h, \omega_o)$ centered around outgoing direction ω_o, the minimum $\min\{p(h, \omega_o), p(h, \omega_i)\}$ of both a distribution centered around outgoing and one centered around incoming direction ω_i is used. Second, the division by the cosine of the angle between incoming direction and normal, $\cos(\theta_i)$, is replaced by a division by the maximum of cosines of both incoming and outgoing directions $\max\{\cos(\theta_i), \cos(\theta_o)\}$. The exponent for the disk distribution is computed as $exponent = 2/roughness^2$.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

handle – Name to provide access to this component for use in an MDL integration.

21.1.4   Measured interaction

Measured BSDF data can contain the measured information for the surface reflection behavior, the surface transmission behavior, or both. The following BSDF selects those depending on the additional `mode` parameter. It is an error if the `mode` parameter selects a mode for which no data is provided in the measurement.

```
bool bsdf_measurement_isvalid(
    uniform bsdf_measurement measurement
) uniform
```
Returns `true` if the value of `measurement` is a valid BSDF measurement reference and `false` otherwise.

```
bsdf measured_bsdf(
   uniform bsdf_measurement measurement,
   uniform float            multiplier  = 1.0,
   uniform scatter_mode     mode        = scatter_reflect,
   uniform string           handle      = ""
);
```

General isotropic reflection and transmission based on measured data.

measurement – Measured BSDF data.

multiplier – Non-negative factor to scale the measurement. Scaling is limited to the maximum scale where an albedo of one is reached for a particular direction and larger factors will not scale the measurement any further.

mode – One of three values: `scatter_reflect`, `scatter_transmit`, or (for both) `scatter_reflect_transmit`.

handle – Name to provide access to this component for use in an MDL integration.

21.1.5 Alternative distribution functions

The distribution functions in the previous sections define the recommended building blocks for the diffuse, glossy, specular, and measured surface interactions. For advanced uses, such as matching another implementation, MDL provides the following alternative distribution functions for glossy interactions. They have compatible parameters to the `simple_glossy_bsdf` distribution function from Section 21.1.3. The first four support transmission, the last one does not.

```
bsdf microfacet_beckmann_smith_bsdf(
  float                 roughness_u,
  float                 roughness_v       = roughness_u,
  color                 tint              = color(1.0),
  color                 multiscatter_tint = color(0.0),
  float3                tangent_u         = state::texture_tangent_u(0),
  uniform scatter_mode mode               = scatter_reflect,
  uniform string       handle             = ""
);
```

Glossy reflection and transmission based on a microfacet model [7] using a Beckmann distribution and a Smith shadowing term [9]. Becomes black in transmission mode if the ior values indicate total interior reflection.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

handle – Name to provide access to this component for use in an MDL integration.

```
bsdf microfacet_ggx_smith_bsdf(
  float                   roughness_u,
  float                   roughness_v       = roughness_u,
  color                   tint              = color(1.0),
  color                   multiscatter_tint = color(0.0),
  float3                  tangent_u         = state::texture_tangent_u(0),
  uniform scatter_mode    mode              = scatter_reflect,
  uniform string          handle            = ""
);
```

Glossy reflection and transmission based on a microfacet model [7] using a GGX distribution and a Smith shadowing term [9]. Becomes black in transmission mode if the ior values indicate total interior reflection.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

handle – Name to provide access to this component for use in an MDL integration.

```
bsdf microfacet_beckmann_vcavities_bsdf(
  float               roughness_u,
  float               roughness_v       = roughness_u,
  color               tint              = color(1.0),
  color               multiscatter_tint = color(0.0),
  float3              tangent_u         = state::texture_tangent_u(0),
  uniform scatter_mode mode             = scatter_reflect,
  uniform string      handle            = ""
);
```

Glossy reflection and transmission based on a microfacet model [7] using a Beckmann distribution and a v-cavities shadowing term [9]. Becomes black in transmission mode if the ior values indicate total interior reflection.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

handle – Name to provide access to this component for use in an MDL integration.

```
bsdf microfacet_ggx_vcavities_bsdf(
  float                  roughness_u,
  float                  roughness_v        = roughness_u,
  color                  tint               = color(1.0),
  color                  multiscatter_tint  = color(0.0),
  float3                 tangent_u          = state::texture_tangent_u(0),
  uniform scatter_mode   mode               = scatter_reflect,
  uniform string         handle             = ""
);
```

Glossy reflection and transmission based on a microfacet model [7] using a GGX distribution and a v-cavities shadowing term [9]. Becomes black in transmission mode if the ior values indicate total interior reflection.

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

mode – One of three values: scatter_reflect, scatter_transmit, or (for both) scatter_reflect_transmit.

handle – Name to provide access to this component for use in an MDL integration.

```
bsdf ward_geisler_moroder_bsdf(
  float           roughness_u,
  float           roughness_v        = roughness_u,
  color           tint               = color(1.0),
  color           multiscatter_tint  = color(0.0),
  float3          tangent_u          = state::texture_tangent_u(0),
  uniform string  handle             = ""
);
```

Glossy reflection based on the Ward BRDF model with bounded albedo [13].

roughness_u – Roughness coefficient in the u direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

roughness_v – Roughness coefficient in the v direction. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

tangent_u – The tangent in the u direction, in internal space.

handle – Name to provide access to this component for use in an MDL integration.

21.2   Light emission

This section documents the elemental *emission distribution function* (EDF) models defined in MDL and their input parameters.

Additionally, the following supportive functions on light profiles are available in the `df` module.

`float light_profile_power(`
    `uniform light_profile profile`
`) uniform`
	Returns the power emitted by this light profile. A lookup on an invalid light profile reference returns zero.

`float light_profile_maximum(`
    `uniform light_profile profile`
`) uniform`
	Returns the maximum intensity in this light profile. A lookup on an invalid light profile reference returns zero.

`bool light_profile_isvalid(`
    `uniform light_profile profile`
`) uniform`
	Returns `true` if the value of `profile` is a valid light profile reference and `false` otherwise.

```
edf diffuse_edf(
  uniform string handle = ""
);
```

Uniform light emission in all directions.

   `handle` – Name to provide access to this component for use in an MDL integration.

```
edf spot_edf(
  uniform float    exponent,
  uniform float    spread              = math::PI,
  uniform bool     global_distribution = true,
  uniform float3x3 global_frame        = float3x3(1.0),
  uniform string   handle              = ""
);
```

Exponentiated cosine weighting for spotlight. The spot light is oriented along the positive z-axis.

`exponent` –	Non-negative exponent for cosine of the angle between axis and sample point.
`spread` –	Angle of the cone to which the cosine distribution is restricted. The hemispherical domain for the distribution is rescaled to this cone. Range: $[0, \pi]$
`global_distribution` –	If `true`, the global coordinate system defines the orientation of light distribution. Otherwise, it is oriented along the local tangent space.
`global_frame` –	Orthonormal coordinate system that defines the orientation of the light distribution with respect to the object space. In other words, multiplying a direction in the coordinate frame of the light distribution with this matrix transforms it into object space.
`handle` –	Name to provide access to this component for use in an MDL integration.

```
edf measured_edf(
  uniform light_profile profile,
  uniform float         multiplier        = 1.0,
  uniform bool          global_distribution = true,
  uniform float3x3      global_frame      = float3x3(1.0),
  float3                tangent_u         = state::texture_tangent_u(0),
  uniform string        handle            = ""
);
```

Light distribution defined by a profile.

profile –	Definition of light distribution.
multiplier –	Non-negative factor to scale the light distribution intensity.
global_distribution –	If `true`, the global coordinate system defines the orientation of light distribution. Otherwise, it is oriented along the local tangent space defined by the `tangent_u` parameter.
global_frame –	Orthonormal coordinate system that defines the orientation of the light distribution with respect to the object space. In other words, multiplying a direction in the coordinate frame of the light distribution with this matrix transforms it into object space.
tangent_u –	The tangent in the u direction, in internal space.
handle –	Name to provide access to this component for use in an MDL integration.

21.3   Volume scattering

This section documents the elemental *volume distribution function* (VDF) models defined in MDL and their input parameters.

```
vdf anisotropic_vdf(
  float          directional_bias = 0.0,
  uniform string handle           = ""
);
```

Volume light distribution with directional bias.

directional_bias –	Influence of light direction on scattering. Range: $[-1,1]$, with 0 specifying isotropic behavior, 1 forward scattering, and -1 back scattering.
handle –	Name to provide access to this component for use in an MDL integration.

```
vdf fog_vdf(
  float          particle_size = 8.0,
  uniform string handle        = ""
);
```

Volume light distribution based on an approximation of the Mie scattering function [14] particularly suitable for fog or cloud-like media.

particle_size – Average diameter of the particle size distribution in micrometer.

handle – Name to provide access to this component for use in an MDL integration.

21.4   Hair bidirectional scattering distribution functions

This section documents the elemental *hair bidirectional scattering distribution function* (hair BSDF) models defined in MDL and their input parameters. Defining an instance of these hair BSDF models uses the

syntax of a function returning a `hair_bsdf`, which is not allowed elsewhere in MDL.

```
hair_bsdf chiang_hair_bsdf(
    float          diffuse_reflection_weight = 0.0,
    color          diffuse_reflection_tint   = color(1.0),
    float2         roughness_R               = float2(0.0),
    float2         roughness_TT              = roughness_R,
    float2         roughness_TRT             = roughness_TT,
    float          cuticle_angle             = 0.0,
    color          absorption_coefficient    = color(0.0),
    float          ior                       = 1.55,
    uniform string handle                    = ""
);
```

Aggregated reflective and transmissive scattering based on the Chiang et al. hair shading model [15] combined with a weighted diffuse reflection component. This hair shading model categorizes the light paths according to the number of internal reflections. The first three categories (and their lobes) are labeled based on event types as R, TT, and TRT, where R denotes a reflection event and T denotes a transmission event. The first three are modeled as separate lobes with roughness parameters along the longitudinal and azimuthal directions, while all longer paths are implicitly accounted for in a fourth lobe in the model without additional parameters; the longitudinal roughness of the fourth lobe is set to the one of the third lobe, while the model needs no roughness parameter for the azimuthal direction.

diffuse_reflection_weight – Weight of the additional diffuse reflection component. The hair shading model is weighted with $(1 - weight)$.

diffuse_reflection_tint – Tint of the additional diffuse reflection component.

roughness_R – Longitudinal and azimuthal roughness (v, s) for the first R-lobe. Range: $[0, \infty)^2$, with $(0, 0)$ specifying pure specular scattering.

roughness_TT – Longitudinal and azimuthal roughness (v, s) for the second TT-lobe. Range: $[0, \infty)^2$, with $(0, 0)$ specifying pure specular scattering.

roughness_TRT – Longitudinal and azimuthal roughness (v, s) for the third TRT-lobe. Range: $[0, \infty)^2$, with $(0, 0)$ specifying pure specular scattering.

cuticle_angle – Cuticle angle in radians, positive angles tilt the scales towards the root of the fiber. Range: $(-\frac{\pi}{2}, \frac{\pi}{2})$.

absorption_coefficient – Absorption coefficient normalized to the hair fiber diameter.

ior – Index of refraction, with 1.55 being the value for keratin as default.

handle – Name to provide access to this component for use in an MDL integration.

21.5 Distribution function modifiers

Distribution function modifiers accept another distribution function as input parameter and change their behavior, such as changing its overall color, adding a directional-dependent thin-film effect, or attenuating

them in a directional dependent way, to form a new distribution function.

```
bsdf tint(
    color         tint,
    bsdf          base
);
edf tint(
    color tint,
    edf           base
);
vdf tint(
    color         tint,
    vdf           base
);
hair_bsdf tint(
    color         tint,
    hair_bsdf     base
);
```

Tint the result of an elemental or compound distribution function with an additional color.

  `tint` – Scaling factor, defined as a color, multiplied by the result of the distribution function.

  `base` – Input distribution function.

```
bsdf tint(
  color reflection_tint,
  color transmission_tint,
  bsdf  base
);
```

Tint the result of an elemental or compound BSDF with separate color factors for reflective and transmissive light paths.

  `reflection_tint` – Scaling factor, defined as a color, multiplied by the result of the reflective light paths of the `base` BSDF.

  `transmission_tint` – Scaling factor, defined as a color, multiplied by the result of the transmissive light paths of the `base` BSDF.

  `base` – Input BSDF.

```
bsdf thin_film(
  float thickness,
  color ior,
  bsdf  base
);
```

Add reflective thin-film interference color to an elemental or compound BSDF. This modifier affects only BSDFs that have a Fresnel term, which are the `fresnel_factor`, `fresnel_layer`, `color_fresnel_layer`, and all microfacet models with the scatter mode set to `scatter_reflect_transmit`, as well as `custom_curve_layer`, `color_custom_curve_layer` and `directional_factor`. And it affects only BSDFs if they are directly the argument to the `base` parameter.

A `custom_curve_layer` as base BSDF is handled like a Fresnel layer with the IOR derived from the `normal_reflectivity` parameter R_0: $\text{IOR} = (1 + \sqrt{R_0})/(1 - \sqrt{R_0})$.

A `directional_factor` as base BSDF is handled as an approximation of the `fresnel_factor` using Gulbrandsen's formulas in [16] to compute the complex IOR.

> `thickness` – Thickness of thin-film layer in nanometer [nm].
>
> `ior` – Index of refraction.
>
> `base` – Base BSDF.

```
bsdf fresnel_factor(
  color ior,
  color extinction_coefficient,
  bsdf  base                      = bsdf()
);
```

Modifier weighting a base BSDF based on the Fresnel reflection equation for a complex number IOR, comprising a real number IOR and an extinction coefficient. This modifier is useful to model the reflectance behavior of conductors and semiconductors.

> `ior` – The IOR.
>
> `extinction_coefficient` – The extinction coefficient.
>
> `base` – Base BSDF.

```
bsdf directional_factor(
  color                 normal_tint  = color(1.0),
  color                 grazing_tint = color(1.0),
  float                 exponent     = 5.0,
  bsdf                  base         = bsdf()
);
edf directional_factor(
  color                 normal_tint  = color(1.0),
  color                 grazing_tint = color(1.0),
  float                 exponent     = 5.0,
  edf                   base         = edf()
);
```

Directional modifier.

normal_tint – Color scaling factor at the normal.

grazing_tint – Color scaling factor at the grazing angle.

exponent – Exponent for directional factor. Default value (5.0) is from Schlick's approximation.

base – Base BSDF or EDF to be modified by directional factor.

```
bsdf measured_curve_factor(
  color[<N>] curve_values,
  bsdf       base          = bsdf()
);
```

Modifier weighting a base BSDF based on a measured reflection curve.

curve_values – Measured data for the reflection behavior. A 1-d function measured in the pre-image range from zero to Pi/2 with equally spaced measured reflectance values.

base – Base BSDF to be modified by the measured reflectance curve.

```
bsdf measured_factor(
  uniform texture_2d values,
  bsdf               base    = bsdf()
);
```

Modifier weighting a base BSDF based on measured reflection values.

The reflectance values may be larger than one. In this case, this distribution function does not protect against energy creation and it is in the responsibility of the material author that the material definition as a whole does not create energy. Failing to do so results in undefined behavior.

values – Measured data of type color for the reflection behavior. A 2-d function measured in the pre-image range $[0, \pi/2]^2$ with equally spaced reflectance values, where the texture-space u-coordinate corresponds to the angle α between the incoming direction and the half-vector h from the microfacet model, and the texture-space v-coordinate corresponds to the angle β between the half-vector h and the shading surface normal.

base – Base BSDF to be modified by the measured reflectance values.

```
bsdf sheen_bsdf(
  float          roughness,
  color          tint             = color(1.0),
  color          multiscatter_tint = color(0.0),
  bsdf           multiscatter     = df::diffuse_reflection_bsdf(),
  uniform string handle           = ""
);
```

Sheen reflection based on a microfacet model [7] using a exponentiated sinusoidal distribution [11] and a v-cavities shadowing term [9].

roughness – Roughness coefficient. Range: $[0, \infty)$, with 0 specifying pure specular reflection.

tint – Scaling factor, defined as a color, multiplied by the result of the distribution function.

multiscatter_tint – Scaling factor, defined as a color, of the default diffuse multiscattering compensation, color(0.0) does not add any, color(1.0) fully compensates the energy loss.

multiscatter – Base BSDF below the sheen component. The default is the standard diffuse BSDF for multiscattering compensation.

handle – Name to provide access to this component for use in an MDL integration.

21.6   Distribution function combiners

Distribution function combiners accept one or more distribution functions and combine them in a weighted, possibly directional dependent way to form a new combined distribution function.

21.6.1   Mixing distribution functions

Mixers combine distribution functions as a weighted sum to form a new distribution function. The sum of the weights should not exceed one and in case it does, the weights are either normalized or clamped, depending on the kind of mixer chosen.

The weights in a mixer can be all scalar, i.e., of type float, or of type color.

Scalar weights are combined with the affected distribution functions in values of the following structure types.

```
struct bsdf_component {
    float weight    = 0.0;
    bsdf  component = bsdf();
};
struct edf_component {
    float weight    = 0.0;
    edf   component = edf();
};
struct vdf_component {
    float weight    = 0.0;
    vdf   component = vdf();
};
```

Component in a scalar mixing operation.

weight – Scaling factor for the effect of the component in the mixing operation. Range: $[0, \infty)$.

component – Distribution function defining the operation of the component.

Color weights are combined with the affected distribution functions in values of the following structure types. Note: There is no component for color weights with a VDF because there is no color mixer for VDFs.

```
struct color_bsdf_component {
    color weight    = color(0.0);
    bsdf  component = bsdf();
};
struct color_edf_component {
    color weight    = color(0.0);
    edf   component = edf();
};
struct color_vdf_component {
    color weight    = color(0.0);
    vdf   component = vdf();
};
```

Component in a color mixing operation.

weight – Scaling factor for the effect of the component in the mixing operation. Range: $[color(0), color(\infty))$.

component – Distribution function defining the operation of the component.

```
bsdf normalized_mix(
    bsdf_component[<N>] components
);
edf normalized_mix(
    edf_component[<N>] components
);
vdf normalized_mix(
    vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the scalar weights defined in the components. If the sum of the weights exceeds 1.0, they are normalized.

 `components` − Array of distribution function components combined by the mix.

```
bsdf color_normalized_mix(
    color_bsdf_component[<N>] components
);
edf color_normalized_mix(
    color_edf_component[<N>] components
);
vdf color_normalized_mix(
    color_vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the color weights defined in the components. If the sum of the weights exceeds color(1) anywhere, the weights are normalized by dividing them equally by the maximum of this sum.

 `components` − Array of distribution function components combined by the mix.

```
bsdf clamped_mix(
    bsdf_component[<N>] components
);
edf clamped_mix(
    edf_component[<N>] components
);
vdf clamped_mix(
    vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the scalar weights defined in the components. Distribution functions and weights are summed in the order they are given. Once a component weight would cause the sum to exceed 1.0, it is replaced with the result of subtracting the sum from 1.0. All subsequent weights are then set to 0.0.

 `components` − Array of distribution function components combined by the mix.

```
bsdf color_clamped_mix(
    color_bsdf_component[<N>] components
);
edf color_clamped_mix(
    color_edf_component[<N>] components
);
vdf color_clamped_mix(
    color_vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the color weights defined in the components. Distribution functions and weights are summed in the order they are given. Once a component weight would cause the sum to exceed color(1) anywhere in the spectrum, it is clamped such that the sum equals to one in places where it would have exceeded color(1).

  `components` − Array of distribution function components combined by the mix.

```
bsdf unbounded_mix(
    bsdf_component[<N>] components
);
edf unbounded_mix(
    edf_component[<N>] components
);
vdf unbounded_mix(
    vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the scalar weights defined in the components. This distribution function does not protect against energy creation unlike `clamped_mix` or `normalized_mix`. It is in the responsibility of the material author that the material definition as a whole does not create energy. Failing to do so results in undefined behavior.

  `components` − Array of distribution function components combined by the mix.

```
bsdf color_unbounded_mix(
    color_bsdf_component[<N>] components
);
edf color_unbounded_mix(
    color_edf_component[<N>] components
);
vdf color_unbounded_mix(
    color_vdf_component[<N>] components
);
```

Mix `N` elemental or compound distribution functions based on the color weights defined in the components. This distribution function does not protect against energy creation unlike `color_clamped_mix` or `color_normalized_mix`. It is in the responsibility of the material author that the material definition as a whole does not create energy. Failing to do so results in undefined behavior.

  `components` − Array of distribution function components combined by the mix.

21.6.2   Layering distribution functions

Layerers combine distribution functions by logically layering one distribution function over another. A weight controls the contribution of the top layer versus the base layer, which is weighted with one minus the weight. The weight can be a directional dependent weight, depending on the specific kind of layerer chosen.

The weight of a layerer can be a scalar, i.e., of type float, or of type color.

```
bsdf weighted_layer(
  float  weight
  bsdf   layer
  bsdf   base  = bsdf(),
  float3 normal = state::normal()
);
```

Add an elemental or compound BSDF as a layer on top of another elemental or compound BSDF according to `weight`. The base is weighted with `1-weight`.

  weight – Factor for `layer`. Range: $[0, 1]$. Values outside of the range are clamped to this range.

   layer – Layer to add to the `base` BSDF.

    base – Base BSDF.

  normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf color_weighted_layer(
  color  weight
  bsdf   layer
  bsdf   base  = bsdf(),
  float3 normal = state::normal()
);
```

Add an elemental or compound BSDF as a layer on top of another elemental or compound BSDF according to `weight`. The base is weighted with `color(1)-weight`.

  weight – Factor for `layer`. Range: $[color(0), color(1)]$. Values outside of the range are clamped to this range.

   layer – Layer to add to the `base` BSDF.

    base – Base BSDF.

  normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf fresnel_layer(
  float  ior,
  float  weight = 1.0,
  bsdf   layer  = bsdf(),
  bsdf   base   = bsdf(),
  float3 normal = state::normal()
);
```

Add an elemental or compound BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a Fresnel term using a dedicated index of refraction for the layer. The base is weighted with `1-(weight*fresnel(ior))`.

      ior – Index of refraction.

weight – Factor for `layer`. Range: $[0,1]$. Values outside of the range are clamped to this range.

  layer – Layer to add to the `base` BSDF.

   base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf color_fresnel_layer(
  color  ior,
  color  weight = color(1.0),
  bsdf   layer  = bsdf(),
  bsdf   base   = bsdf(),
  float3 normal = state::normal()
);
```

Add an elemental or compound BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a Fresnel term using a dedicated index of refraction for the layer. The base is weighted with `color(1)-(weight*fresnel(ior))`.

      ior – Index of refraction.

weight – Factor for `layer`. Range: $[color(0), color(1)]$. Values outside of the range are clamped to this range.

  layer – Layer to add to the `base` BSDF.

   base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf custom_curve_layer(
  float  normal_reflectivity,
  float  grazing_reflectivity = 1.0,
  float  exponent             = 5.0,
  float  weight               = 1.0,
  bsdf   layer                = bsdf(),
  bsdf   base                 = bsdf(),
  float3 normal               = state::normal()
);
```

BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a Schlick-style directional-dependent curve function. The base is weighted with `1-(weight*curve())`.

normal_reflectivity – Reflectivity for angle of incidence normal to the surface.

grazing_reflectivity – Reflectivity for angle of incidence at 90 degrees to surface normal.

exponent – Exponent for Schlick's approximation.

weight – Factor for `layer`. Range: $[0, 1]$. Values outside of the range are clamped to this range.

layer – Layer to add to the `base` BSDF.

base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf color_custom_curve_layer(
  color  normal_reflectivity,
  color  grazing_reflectivity = color(1.0),
  float  exponent             = 5.0,
  color  weight               = color(1.0),
  bsdf   layer                = bsdf(),
  bsdf   base                 = bsdf(),
  float3 normal               = state::normal()
);
```

BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a Schlick-style directional-dependent curve function. The base is weighted with `color(1)-(weight*curve())`.

normal_reflectivity – Reflectivity for angle of incidence normal to the surface.

grazing_reflectivity – Reflectivity for angle of incidence at 90 degrees to surface normal.

exponent – Exponent for Schlick's approximation.

weight – Factor for `layer`. Range: $[color(0), color(1)]$. Values outside of the range are clamped to this range.

layer – Layer to add to the `base` BSDF.

base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf measured_curve_layer(
  color[<N>] curve_values,
  float      weight        = 1.0,
  bsdf       layer         = bsdf(),
  bsdf       base          = bsdf(),
  float3     normal        = state::normal()
);
```

BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a measured reflectance curve. The base is weighted with `1-(weight*curve())`.

curve_values – Measured data for the reflection behavior. A 1-d function measured in the pre-image range from zero to Pi/2 with equally spaced measured reflectance values.

weight – Factor for `layer`. Range: $[0, 1]$. Values outside of the range are clamped to this range.

layer – Layer to add to the `base` BSDF.

base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

```
bsdf color_measured_curve_layer(
  color[<N>] curve_values,
  color      weight        = color(1.0),
  bsdf       layer         = bsdf(),
  bsdf       base          = bsdf(),
  float3     normal        = state::normal()
);
```

BSDF as a layer on top of another elemental or compound BSDF according to `weight` and a measured reflectance curve. The base is weighted with `color(1)-(weight*curve())`.

curve_values – Measured data for the reflection behavior. A 1-d function measured in the pre-image range from zero to Pi/2 with equally spaced measured reflectance values.

weight – Factor for `layer`. Range: $[color(0), color(1)]$. Values outside of the range are clamped to this range.

layer – Layer to add to the `base` BSDF.

base – Base BSDF.

normal – Surface normal vector, in internal space, applied to top layer.

---

22   Appendix A – The syntax of MDL

This section describes the syntactic structure of MDL in a grammar using Wirth's extensions of Backus Normal Form. The left-hand side of a production is separated from the right hand side by a colon. Alternatives are separated by a vertical bar. Optional items are enclosed in square brackets. Curly braces indicate that the enclosed item may be repeated zero or more times.

Non-terminal and meta-symbols are given in *italic* font. Terminal symbols except identifiers, typenames, and literals are given in `teletype` font. The definition for the terminal symbols *identifier*, *typename*, *boolean_literal*, *integer_literal*, *float_literal*, and *string_literal* is given in Section 5 with the other parts of the lexical structure of MDL.

This grammar is an incomplete description of MDL, defining a superset of all legal MDL programs. Further restrictions required by legal MDL programs are included in corresponding chapters of this document. The page number of the section that describes the use of the syntax rule in MDL programs is listed to the right.

mdl	:	*mdl_version* { *import* } [`module` *annotation_block* `;`] { [`export`] *global_declaration* }	13, 83 , 85
boolean_literal	:	`true` | `false`	18
enum_literal	:	`intensity_radiant_exitance` | `intensity_power`	18
integer_literal	:	*INTEGER_LITERAL*	18
floating_literal	:	*FLOATING_LITERAL*	18
string_literal	:	*STRING_LITERAL*	18
mdl_version	:	`mdl` *floating_literal* `;`	13
simple_name	:	*IDENT*	81
import_path	:	({ `.` `.` `::` } | [`.` `::`] | [`::`]) *module_name*	81
qualified_import	:	*import_path* `::` (`*` | *simple_name*)	81
module_name	:	*path_identifier* { `::` *path_identifier* }	81
path_identifier	:	*unicode_identifier* | *simple_name*	81
unicode_identifier	:	*UNICODE_IDENTIFIER*	
qualified_name	:	[[`::`] *module_name* `::`] *simple_name*	
frequency_qualifier	:	`varying` | `uniform`	21

relative_type	:	`bool` | `bool2` | `bool3` | `bool4`	21
		| `int` | `int2` | `int3` | `int4`	
		| `float` | `float2` | `float3` | `float4`	
		| `float2x2` | `float2x3` | `float2x4`	
		| `float3x2` | `float3x3` | `float3x4`	
		| `float4x2` | `float4x3` | `float4x4`	
		| `double` | `double2` | `double3` | `double4`	
		| `double2x2` | `double2x3` | `double2x4`	
		| `double3x2` | `double3x3` | `double3x4`	
		| `double4x2` | `double4x3` | `double4x4`	
		| `color` | `string` | `bsdf` | `edf` | `vdf` | `hair_bsdf`	
		| `light_profile` | `bsdf_measurement`	
		| `material` | `material_emission` | `material_geometry`	
		| `material_surface` | `material_volume` | `intensity_mode`	
		| `texture_2d` | `texture_3d` | `texture_cube` | `texture_ptex`	
		| *IDENT* [`::` *relative_type*]	
simple_type	:	[`::`] *relative_type*	21
array_type	:	*simple_type* [`[` [*conditional_expression* | `<` *simple_name* `>`] `]`]	21, 43
type	:	[*frequency_qualifier*] (`auto` | *array_type*)	21
parameter	:	*type* *simple_name* [`=` *assignment_expression*]	59, 60, 73
		[*annotation_block*]	
parameter_list	:	([*parameter* { `,` *parameter* } [`,`]])	59, 73
positional_argument	:	*assignment_expression*	59
named_argument	:	*simple_name* `:` *assignment_expression*	59
argument_list	:	(	59
		[*named_argument* { `,` *named_argument* } [`,`]	
		| *positional_argument* { `,` *positional_argument* }	
		{ `,` *named_argument* } [`,`]	
		]	
		)	
import	:	`import` *qualified_import* { `,` *qualified_import* } `;`	13, 81, 83
		| [`export`] `using` *import_path*	
		`import` (`*` | *simple_name* { `,` *simple_name* }) `;`	
global_declaration	:	*annotation_declaration*	13
		| *constant_declaration*	
		| *type_declaration*	
		| *function_declaration*	
annotation_declaration	:	`annotation` *simple_name* *parameter_list* [*annotation_block*] `;`	79
constant_declarator	:	*simple_name* (*argument_list* | `=` *conditional_expression*)	26
		[*annotation_block*]	

constant_declaration	:	const *array_type constant_declarator* { , *constant_declarator* } ;	26
type_declaration	:	*alias_type_declaration*	55
		| *struct_type_declaration*	
		| *enum_type_declaration*	
alias_type_declaration	:	typedef *type simple_name* ;	53
struct_field_declarator	:	*type simple_name* [= *expression*]	47
		[*annotation_block*] ;	
struct_type_declaration	:	struct *simple_name* [*annotation_block*]	
		{ {*struct_field_declarator*} } ;	47
enum_value_declarator	:	*simple_name* [= *assignment_expression*] [*annotation_block*]	51
enum_type_declaration	:	enum *simple_name* [*annotation_block*] {	51
		enum_value_declarator { , *enum_value_declarator*} [,]	
		} ;	
variable_declarator	:	*simple_name* [*argument_list* | = *assignment_expression*]	22
		[*annotation_block*]	
variable_declaration	:	*type variable_declarator*	22
		{ , *variable_declarator* } ;	
function_declaration	:	*type* [*annotation_block*] *simple_name*	59, 65, 66, 73, 74
		(*parameter_list* [*frequency_qualifier*] [*annotation_block*]	
		(;	
		| *compound_statement*	
		| = *expression* ;	
		)	
		| (*) [*annotation_block*] = *expression* ;	
		)	
annotation_block	:	[[*annotation* { , *annotation*} [,]]]	79
annotation	:	*qualified_name argument_list*	79
statement	:	*compound_statement*	55
		| *type_declaration*	
		| *constant_declaration*	
		| *variable_declaration*	
		| *expression_statement*	
		| *if_statement*	
		| *switch_statement*	
		| *while_statement*	
		| *do_statement*	
		| *for_statement*	
		| *break_statement*	
		| *continue_statement*	
		| *return_statement*	

compound_statement	:	{ {*statement*} }	55
expression_statement	:	[*expression*] ;	25
if_statement	:	if (*expression*) *statement* [else *statement*]	56
switch_statement	:	switch (*expression*) { {*switch_case*} }	56
switch_case	:	case *expression* : {*statement*} | default : {*statement*}	56
while_statement	:	while (*expression*) *statement*	55
do_statement	:	do *statement* while (*expression*) ;	55
for_statement	:	for ((*variable_declaration* | *expression_statement*)	55
		[*expression*] ; [*expression*])	
		statement	
break_statement	:	break ;	57
continue_statement	:	continue ;	57
return_statement	:	return *expression* ;	57
literal_expression	:	*boolean_literal*	18
		| *enum_literal*	
		| *integer_literal*	
		| *floating_literal*	
		| *string_literal* {*string_literal*}	
primary_expression	:	*literal_expression*	25, 68
		| *simple_type* [[ ]]	
		| (*expression*)	
		| cast < *array_type* > (*unary_expression*)	
		| operator *operator_function_op argument_list*	
operator_function_op	:	[] | ! | ~ | + | – | * | / | % | << | >> | >>> | < | <= | > | >= | == | !=	25, 68
		| & | ^ | | | && | || | ?	
postfix_expression	:	*primary_expression*	24, 59
		{++	
		| --	
		| . *simple_name*	
		| *argument_list*	
		| [*expression*]	
		}	
let_expression	:	let	24, 67, 75
		(*variable_declaration*	
		| { *variable_declaration* {*variable_declaration*} }	
		)	
		in *assignment_expression*	

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unary_expression	:	*postfix_expression*	24
		| (~ | ! | + | − | ++ | −−) *unary_expression*	
		| *let_expression*	
multiplicative_expression	:	*unary_expression* {(* | / | %) *unary_expression* }	24
additive_expression	:	*multiplicative_expression* {(+ | −) *multiplicative_expression* }	24
shift_expression	:	*additive_expression* {(<< | >> | >>>) *additive_expression* }	24
relational_expression	:	*shift_expression* {(< | <= | >= | >) *shift_expression* }	24
equality_expression	:	*relational_expression* {(== | !=) *relational_expression* }	24
and_expression	:	*equality_expression* { & *equality_expression* }	24
exclusive_or_expression	:	*and_expression* { ^ *and_expression* }	24
inclusive_or_expression	:	*exclusive_or_expression* { | *exclusive_or_expression* }	24
logical_and_expression	:	*inclusive_or_expression* { && *inclusive_or_expression* }	24
logical_or_expression	:	*logical_and_expression* { || *logical_and_expression* }	24
conditional_expression	:	*logical_or_expression* [? *expression* : *assignment_expression*]	24
assignment_operator	:	= | *= | /= | %= | += | −= | <<= | >>= | >>>= | &= | ^= | |=	24
assignment_expression	:	*logical_or_expression*	24
		[? *expression* : *assignment_expression*	
		| *assignment_operator* *assignment_expression*	
		]	
expression	:	*assignment_expression* { , *assignment_expression* }	24

23 Appendix B – MBSDF file format

The MBSDF file format stores the data for a measurement of a bidirectional scattering distribution function (BSDF). A BSDF consist of two parts: a bidirectional reflection distribution function (BRDF) and a bidirectional transmission distribution function (BTDF). A measurement can contain either one or both.

This section documents version 1 of the MBSDF file format.

The filename extension is `.mbsdf`.

The file format starts with a file header and has one or two BSDF data blocks. The file header is readable ASCII text while the BSDF data blocks are binary data after a text identifier. The BRDF data comes before the BTDF data if both are present. The second block is directly appended to the first.

The basic entities to describe the format are the following types and their file storage size and description:

Type	Bytes	Storage
string	variable	string restricted to printable ASCII characters and terminated by '\n'.
uint	4	binary storage of a 32-bit unsigned integer value in little-endian ordering
float	4	single-precision floating-point number as defined in IEEE-754 with binary storage in little-endian ordering.

A type followed by an array-like brackets '[ ]' denote a sequence of zero or more occurrences of this type.

23.1 Header block

The header block starts with a magic identifier string including a version number followed by a sequence of strings for meta-data.

Type	Bytes	Value	Comment
string	20	`NVIDIA ARC MBSDF V1\n`	magic identifier including file format version number, terminated by newline.
string[]	variable	meta-data	sequence of zero or more strings, each representing a key-value pair in the format `<key>="<value>"\n`. The sequence \n encodes a newline character, \" encodes a double quote, and \\ encodes a backslash in the value part. Other escape sequences are not allowed and ignored.

The meta-data can be used to document, for example, a name of the measured material, authorship, copyright, measurement device or date.

23.2 BSDF data block

A BRDF data block starts with an identifier to distinguish between BRDF and BTDF data, followed by the binary data. The identifier terminates with an equal sign before the newline character without a double-quote, which distinguishes it unambiguously from the sequence of meta-data in the header block.
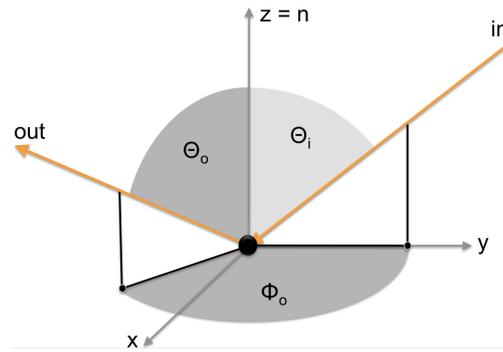
Figure 23.1: The geometry of the angles in a single BRDF measurement for the incoming light direction `in` and outgoing light direction `out`.

Type	Bytes	Value	Comment
string	variable	*IDENT*=\n	identifier to start the binary data block, where the *IDENT* can be `MBSDF_DATA_REFLECTION` or `MBSDF_DATA` for a BRDF block or `MBSDF_DATA_TRANSMISSION` for a BTDF block.
uint	4	T	enum value encoding the type of one measurement: $T = 0$: one float representing a scalar intensity measurement. $T = 1$: three float values representing a sRGB measurement.
uint	4	n_Θ	number of steps used for an equi-spaced angular resolution of Θ_i and Θ_o, greater than zero.
uint	4	n_Φ	number of steps used for an equi-spaced angular resolution of Φ, greater than zero.
float[]	$n_\Phi \cdot n_\Theta \cdot n_\Theta \cdot S$	measured data	S is the size of a single measurement in bytes, i.e., 4 for $T = 0$ and 12 for $T = 1$. The data is stored in the order defined by this indexing offset function: `offset(idx_theta_i, idx_theta_o, idx_phi)` = `idx_theta_i`*n_Φ*n_Θ + `idx_theta_o`*n_Φ + `idx_phi`.

The angular resolution is the same for Θ_i and Θ_o. Both angles are sampled in the range $[0, \pi/2]$, while Φ is sampled in the range $[0, \pi]$.

24   Appendix C – MDL archive file format

MDL archives provide a way of combining a set of MDL packages and modules, as well as resources like textures, into a single file. This allows for easier deployment and versioning.

The MDL archive specification consists of the archive container specification (Section 24.1) and the archive manifest specification (Section 24.2).

24.1   Archive container

Archives act as a virtual extension to the file system. The behavior of an MDL module remains the same, regardless of whether it is placed in an archive or stored directly in the file system.

24.1.1   Contents

An MDL archive encloses a single package, a single module, or a single package with an identically named module on the same level.

If the contained module or package is itself a member of higher level packages, those packages will be present in the form of parent directories in the archive structure.

Below the contained package directory, archives can also contain other files besides MDL modules, most notably resource files such as textures. If a directory contains directly or indirectly an MDL module then the directory must be a legal MDL package (Section 15), i.e., its name must be a legal MDL identifier (Section 5.5).

Each archive must contain exactly one manifest of the type described in Section 24.2.

24.1.2   Name

The file name of an archive consists of the package path of the enclosed package from the search root (exclusive) to the package itself (inclusive). Package names are separated by a dot. The archive file extension is .mdr. For example, consider the following directory structure

```
<search-path-root>
  +--- parent
       +--- m.mdl
       +--- m
            +--- i1.mdl
            +--- i2.mdl
            +--- sub
                 +--- ...
```

where the package m, its identically named module m.mdl, and subpackages will be combined into an archive. The resulting archive, parent.m.mdr, will have the following structure

```
<archive-root>
  +--- MANIFEST
  +--- parent
       +--- m.mdl
       +--- m
            +--- i1.mdl
            +--- i2.mdl
            +--- sub
                 +--- ...
```

The system will reject archives that do not follow this convention.

24.1.3   Installation and use

Archives must be installed in the top level of a search root. Archives found elsewhere will be ignored. The system may issue a warning in that case.

It is an error to duplicate contents of an archive in the same search root as the archive itself. In particular, given an archive with a name ending in `m.mdr`, its content includes either a package `m` or a module `m.mdl` (or both), and neither is allowed to exist in the same search root or in another archive in the same search root, irrespectively of whether actually both or only one exist in the archive. In case of an error, no entity in the archive or in its duplicated contents can be found and used. The rationale here is that to resolve a qualified MDL name and its prefixes, only one archive needs to be inspected per search root and there will not be any conflict with the non-archive packages and modules.

For example, given an archive `a.b.c.mdr`, the following search root structure illustrates the principle error cases:

```
<search-path-root>
  +--- a.b.c.mdr
  +--- a.b.d.mdr        // o.k., ::a::b::d::... resolves uniquely
  +--- a.b.c.e.mdr      // ERROR! ::a::b::c::... is ambigious
  +--- a
      +--- b
          +--- f        // o.k., ::a::b::f::... resolves uniquely
               +...
          +--- c        // ERROR! ::a::b::c::... is ambigious
               +...
          +--- c.mdl    // ERROR! ::a::b::c::... is ambigious
```

24.1.4   File format

Archives consist of an 8 byte marker block immediately followed by a ZIP file [17] with contents described above. The hexadecimal encoding of the marker block is 4D 44 52 00 00 01 00 00. The ZIP version needed to extract each file [17, Section 4.4.3] must not be higher than 2.0.

Texture files (Section 2.3) are stored without compression.

24.2   Archive manifest

The manifest provides meta information about an MDL archive to integrations. The manifest is a plain text UTF-8 [2] file named `MANIFEST` and placed in the root of the archive directory tree. Furthermore, the manifest must be the first file in the archive structure and stored without compression.

24.2.1   Data layout

The manifest file contains a number of key/value pairs. Key and value are separated by the equality sign = and optional white space.

The name of a key is a valid identifier as described in Section 5.5, except that typenames and reserved words are allowed, possibly followed by a sequence of dot and another identifier. Each key must start in the first column of a new line.

Values are arbitrary strings enclosed by double quotes. Values may span several lines. In this case, each line is quoted. Value continuation lines following the key line must be indented by at least one whitespace. Escape sequences \" and \\ are interpreted to mean a literal double quote (rather than the end of the value string) and a literal backslash, respectively. Other escape sequences as described in Section 5.8.5 are retained in the string but do not affect the parsing of the value.

Manifest files may furthermore contain empty lines and comments. Comments are lines starting with the hash character # and extend until the end of the line.

24.2.2   Mandatory fields

The following fields are mandatory. Failure to specify all of the following fields correctly will result in an error and rejection of the archive, except for the case of missing dependencies, which whenever detected at runtime will result in a warning.

`mdl`	Specifies the MDL version of this archive. The version follows that described in Section 4.1. The archive may not contain modules with a higher MDL version. The manifest shall contain exactly one `mdl` field.
`version`	Specifies the version number of the archive contents. The format of the value must follow Semantic Versioning 2.0.0 [4]. Pre-release labels are permitted, e.g., `1.0.0-alpha.1`. Labels for build metadata are not permitted. The manifest shall contain exactly one `version` field.

dependency	Specifies a dependency of the archive's contents on another archive. Multiple dependency fields are used to express multiple dependencies. There is no dependency field if the archive's content does not depend on any other archive. A system shall issue a warning for archives whose dependencies are not satisfied or if dependencies are detected that are missing in the manifest.
	The format is the archive name (see Section 24.1.2) excluding the `.mdr` file extension followed by a space and the required version of the archive. The format of the version must follow Semantic Versioning 2.0.0 [4]. Pre-release labels are permitted, e.g., `1.0.0-alpha.1`. Labels for build metadata are not permitted.
	The version specifies the minimum version that the referenced archive must have to satisfy the dependency. In particular, the dependency is satisfied if the referenced archives's version has the same major number and its minor number, patch number, and pre-release modifier compare equal or higher to the version requested.
	For example, an archive `pkg.example.mdr` with the following version field
	`version="2.1.3"`
	works fine with archives that have dependency fields as follows:
	`dependency="pkg.example 2.0.1"` `dependency="pkg.example 2.1.3"`
	And it warns with archives that have dependency fields as follows, one for a too high version number and one for a non-matching major number:
	`dependency="pkg.example 2.1.4"` ! *warning* `dependency="pkg.example 1.1.3"` ! *warning*
module	Lists all modules in the archive. The value is the fully qualified name of the module. Multiple modules are specified with multiple fields. An MDL archive may have no MDL module in which case there will be no `module` fields and no `exports` fields in the manifest. The list of modules must be correct and complete.
exports.function	Lists all functions exported by the modules in the archive. The value is the fully qualified name of the function. Parameter list and return value are omitted. Multiple exports are specified with multiple fields. The list of exports must be correct and complete.
exports.material	The equivalent of `exports.function` for materials (Section 13).
exports.struct	The equivalent of `exports.function` for structs (Section 8).
exports.enum	The equivalent of `exports.function` for enumerations (Section 9).
exports.const	The equivalent of `exports.function` for global constants (Section 6.8).
exports.annotation	The equivalent of `exports.function` for annotations (Section 14).

The following example shows a small manifest of an archive exporting a single material with a dependency on another archive:

```
# comment in an example MANIFEST
mdl="1.2"
version="1.0.0"
dependency="other_package.example_archive 1.2.3"
module="::example_package::example_module"
exports.material="::example_package::example_module::example_material"
```

24.2.3 Optional fields

The following fields are optional. They define a set of attributes with a common interpretation.

The following fields follow the standard annotations specified in Section 18.

author	Specifies the archive author. Multiple authors are specified with multiple fields.
contributor	Specifies the name of a contributing author. Multiple contributors are specified with multiple fields.
copyright_notice	Specifies copyright information. The manifest shall not contain more than one copyright_notice field.
description	Specifies a description of the archive. The manifest shall not contain more than one description field.
created	Specifies the date on which the archive was created. The format of the string is YYYY-MM-DD[, NOTE], where the trailing note is an arbitrary string. The manifest shall not contain more than one created field.
modified	Specifies the date on which the archive was modified. The format follows that of created. The manifest shall not contain more than one modified field.

25 Appendix D – MDLE file format

The NVIDIA Material Definition Language Encapsulated file format, or MDLE for short, is a container format that stores one MDL function or material with all its dependencies including resources in one file. It is fully self-contained and has no external dependencies except maybe for standard library functions.

25.1 File name and location

MDLE files can have arbitrary file names followed by the file name extension `.mdle`. They can be placed and used anywhere in a file system.

Note: MDLE files deviate from the requirements on MDL files. In particular, MDLE files do not make use of the file path and resolution from Section 2.2 and are not restricted in their name to MDL identifiers (Section 15).

25.2 Container format

MDLE files consist of an eight-byte marker block immediately followed by a sixteen-byte hash block, which is in turn immediately followed by a ZIP file [17]. The hexadecimal encoding of the marker block is 4D 44 4C 45 00 01 00 00, i.e., the marker block starts with the string `"MDLE"` followed by four bytes reserved for future use. Details on the hash block follow below.

The ZIP version needed to extract each file [17, Section 4.4.3] must not be higher than 2.0.

The ZIP-file comment [17, Section 4.4.26] may be used to store the name and version information of the authoring program of this MDLE file as an UTF-8-encoded string [2].

The ZIP file contains a set of standardized files and directories as detailed in Section 25.3. It may contain additional files and directories, where it is recommended to isolate related groups of additional files in their own directory to reduce the risk of name collisions.

All files in the ZIP file must have an MD5 hash value [18] computed and stored in the ZIP-file meta data as an *extra field* [17, Section 4.4.28 and 4.5] per file with the two-byte *Header ID* set to `0x444d` (`"MD"`). The MD5 hash value is stored as 16-byte binary data in the extra field of the local file header.

To identify an MDLE independent of its file name and path in the file system, an additional MD5 hash must be stored as 16-byte binary data in the hash block at the beginning of the MDLE file. This hash value is computed over a sorted list in ascending order of all file paths in the ZIP-file, using the UTF-8 encoding of their relative path in the ZIP-file [17, Section 4.4.17], each file path followed by the individual binary MD5 hash of that file.

Image files, which are, for example, used for textures (Section 2.3) or preview images with the `thumbnail` annotation (Section 18), must be stored without compression in the ZIP file.

25.3 Container content

The ZIP-file must contain a file named `main.mdl`. This file defines the *main module*, which is a regular MDL module (Section 15) with the following restrictions:

1. The module contains an exported function or material named `main`. The behavior of the MDLE file as a whole is defined by this one *main declaration*.

2. All parameters of the main declaration must have default initializers.

3. The main module is written for a top-level placement in a search path, it is not placed inside a package. Thus the fully qualified name of the main declaration is `main::main`.

4. The main module may import declarations from the standard modules (Section 16), but it must not import declarations from any other module, i.e., the full implementation of the main declaration must be in the main module.

5. In consequence, user defined structure types and enumeration types can only be used in the main module if they are also declared in the main module, and they can only be used in the signature of the main declaration if they are also exported from the main module.

6. The parameters of the main declaration can have fully general initializer expressions as permitted by MDL, for example, `state::normal()`. However, in consequence of the import restrictions, non-standard functions or types used in such initializer expressions must be implemented in the main module and exported.

7. All declarations that must be exported only because of a parameter initializer expression of the main declaration must be marked with the `hidden` annotation (Section 18).

8. There should be no other declarations exported from the main module besides those mentioned explicitly in this section. An integration may ignore additionally exported declarations.

9. If a declaration in the main module is the result of a copy or refactoring operation of another declaration, the `origin()` standard annotation (Section 18) shall be set to this original declaration, or the value of its `origin()` annotation if it exists. The value of the `origin()` annotation may be used to identify identical declarations more easily by integrations, but they need also to validate matching signatures and implementations where applicable.

10. The implementation in the main module may reference resource files, i.e., texture (Section 6.14), light profile (Section 6.15), or measured BSDF (Section 6.16) files. The reference to a resource file in the MDL module must be a strict relative file path (Section 2.2).

Resource files used in the main module must be stored in a directory named `resources` in the ZIP file. They must be stored without additional compression of the ZIP file format.

MDLE files may contain preview images, which must be stored in a directory named `thumbnails` in the ZIP file. They must be stored without additional compression of the ZIP file format. Supported image formats are the JPEG or PNG file format as defined in Section 2.3. The image file name must be the module named followed by the previewed declaration name, separated by a dot, and followed by the respective image file format extension, again separated by a dot. For example, the preview image for the main declaration in the PNG format must be named `main.main.png`. The respective declarations in the main module must use the `thumbnail` annotation (Section 18) to reference the preview image.

Note: The canonical preview image file name allows to use preview images without inspecting the MDL module, while the thumbnail annotation in the main module is nonetheless mandated to keep the MDL module standard conforming.

A minimal MDLE file structure in the ZIP file looks as follows:

```
<ZIP-file root>
  +--- main.mdl
```

An example of an MDLE file structure in the ZIP file with a texture, a preview image for the main declaration, a preview image for an additional texture lookup function, and an XLIFF translation to German looks as follows:

```
<ZIP-file root>
  +--- main.mdl
  +--- resources
  |     +--- example_texture.png
  +--- thumbnails
  |     +--- main.main.png
```

```
    |    +--- main.texture_lookup.png
+--- main_de.xlf
```

25.4   Runtime model

Loading an MDLE file shall be equivalent to loading the main module on an otherwise empty system. In particular, loading other MDL modules or MDLE files shall not have an observable influence on the behavior of an MDLE file except possibly for memory and performance behavior.

To insulate an MDLE file from another MDLE file, it is recommended to prefix all runtime identifiers from an MDLE file with a unique identifier for the MDLE file, for example, its full file system path and file name.

A runtime may use the MD5 hash values in the MDLE files to identify identical files and optimize memory and performance behavior of a system. In particular, a runtime can trust the MDL5 hash value and does not have to check for its correctness.

Integrations may use the MDLE file name as a display name for the main declaration if no `display_name` annotation (Section 18) is given explicitly.

The declarations in an MDLE file that are marked with the `hidden` annotation should be excluded from general user-interface selection lists and browsers that are not context-restricted to the respective MDLE file and its main module. On the other hand, for example, a node-graph editor should show the respective nodes where applicable in relation to the main declaration node.

Since MDLE files need to declare all user defined structure types and enumeration types in their main module, these types will never match otherwise identical types in other MDLE files or MDL modules. This prevents the easy assignment of structure values as a whole or enumeration values outside of the boundary of their defining MDLE file.

Note: The `cast` operator (Section 6.5), which enables the assignment between structure equivalent types, allows integrations to offer different assignment behaviors from strict to weak, from automatic to user-controlled and configurable.

25.5   Interoperability between MDLE and MDL

MDLE files are self contained and have no references to nor dependencies on external MDL modules, other MDLE files, nor external resources.

MDL files cannot import MDLE files.

A runtime may use declarations from MDLE files in arguments to MDL declarations, and vice versa may use declarations from MDL files in arguments to MDLE declarations. Such runtime graphs cannot be exported as such into an MDL file nor an MDLE file. They may be exported to other scene graph file formats depending on their capability, or refactoring may be used to create a pure MDLE or a pure MDL file export.

26 Appendix E – MDL internationalization

MDL defines a framework for the internationalization of MDL annotation parameters of type string. The translations are stored in the XLIFF 1.2 file format [19]. Following the standard, XLIFF files use the `.xlf` file name extension. XLIFF files are stored in MDL search paths and can be embedded in MDL archives and MDLE files. Each XLIFF file is specific to a *locale*, i.e., a translation language. The locale must be a 2-letter code defined by the ISO 639-1:2002 standard [20].

26.1 Translated annotation parameters

All annotation parameters of type string can be translated using this framework. In the standard library, translation is limited to the following annotations only (Section 18):

```
anno::display_name      anno::description      anno::copyright_notice
anno::author            anno::contributor      anno::key_words
anno::unused            anno::deprecated       anno::in_group
```

26.2 File names and locations

XLIFF files used for MDL translations are located either in a directory or sub-directory of an MDL search path (Section 2.2), inside an MDL archive file (Section 24), or inside an MDLE file (Section 25). Their file paths are relative to a search root or MDLE ZIP-file content, see Section 26.2.3.

An XLIFF file can be a *module XLIFF file*, which provides translations for one language for an MDL module only, or a *package XLIFF file*, which provides translations for one language for a package with all its modules and sub-packages.

26.2.1 Module XLIFF files

A module XLIFF file is placed in a package or at the root of an MDL search path. Its name is

```
<module>_<locale>.xlf
```

where `<module>` is the MDL module name and `<locale>` is the locale. The file path of the module XLIFF file must be the same as the file path of the module that it applies to.

26.2.2 Package XLIFF files

A package XLIFF file is placed in a package or at the root of an MDL search path. Its name is:

```
<locale>.xlf
```

where `<locale>` is the locale. The file path of the package XLIFF file must be the same as the file path of the package or search root that it applies to.

26.2.3 XLIFF file name resolution

The file paths for XLIFF files are not locations in the file system, but only references in relation to the search paths. The translation of a file path to a file system location is the *file resolution*, which follows the same rules as the file path resolutions for the absolute file paths of an MDL module, see Section 2.2.

This implies that XLIFF files for a module or package do not have to be in the same directory as the MDL module or package itself. For example, the XLIFF file for the module file `m.mdl` located under `<search-path-root-1>` could be located under `<search-path-root-2>`, which can be used to install translation packs in locations independent from the MDL modules themselves:

```
<search-path-root-1>
```

```
    +--- parent
        +--- m.mdl


<search-path-root-2>
  +--- parent
        +--- m_fr.xlf
```

26.2.4   XLIFF files in MDL archives

When provided inside MDL archives (Section 24), XLIFF files follow the same conventions as in a regular package structure with the exception that a package translation file is not allowed in the archive root directory but only below that. A module translation file is allowed in the root directory of an archive.

26.2.5   XLIFF files in MDLE files

The simplified structure of an MDLE file (Section 25) with its single main module allows only for module translation files, which are stored in the root directory of the ZIP-file structure next to the `main.mdl` module.

26.2.6   XLIFF file context

The *XLIFF file context* is a fully qualified name that controls the scope of strings that are translated by this file. The context is defined by the location of the file in relation to its MDL search path root, and analoguously in MDL archive files: A module XLIFF file context is the absolute module name of its respective module, and a package XLIFF file context is the absolute package name of its respective package.

In the following example, the XLIFF file context for `fr.xlf` is `::parent` and the `m_fr.xlf` context is `::parent::m`:

```
<search-path-root>
  +--- parent
        +--- m.mdl
        +--- fr.xlf
        +--- m_fr.xlf
```

The module XLIFF file context of the main module in an MDLE file is `::main`.

26.3   XLIFF elements used for MDL internationalization

XLIFF is an XML-based standard. This framework makes in particular use of the following tag elements and attributes of the XLIFF standard.

26.3.1   Translation units

A translation unit element (`<trans-unit>`) contains a source (`<source>`) and a target (`<target>`) element. A source element defines the string which needs to be translated. A target element represents the result of the translation of the source element in the target language. The required `id` attribute is used to uniquely identify the translation unit within all translation units. The optional note (`<note>`) element can be used to add comments about the translation unit.

26.3.2   Scope of the translation units

The *scope* of a translation unit is a fully qualified MDL name. The scope determines for which MDL elements this translation unit is used for. The scope is either implicit, in which case it is the XLIFF file context, or explicit, in which case it is the group context specified by the resname attribute of a group element.

26.3.3   Groups and group context

The optional group (`<group>`) element specifies a set of elements that should be processed together as a translation unit.

Groups can specify a *group context* with the optional `resname` attribute, which restricts the scope of the translation in this group to a specific MDL element. The group context is a *relative qualified identifier name*, which is the identifier of the MDL element, with module and package names preceding it, all separated by the scope operator '::'. It does not start with a scope operator. The group context is given relative to the XLIFF file position such that the concatenation of the XLIFF file context and the group context, separated by the scope operator '::', form the fully qualified identifier of the MDL element.

The following example MDL file structure illustrates the use of contexts:

```
<search-path-root>
  +--- parent
       +--- example_material.mdl     // contains 'example' material
       +--- example_material_fr.xlf
       +--- fr.xlf
```

The package XLIFF file `fr.xlf` for a French translation uses the `resname` attribute to set the group context and restrict the translation to a material `example` in the `example_material` module:

```
<group resname="example_material::example">
  <trans-unit id="anno_0">
    <source>Example material</source>
    <target>Exemple de matériel</target>
    <note>Description for example_material::example</note>
  </trans-unit>
</group>
```

Setting the group context for the same material in the module XLIFF file `example_material_fr.xlf` for a French translation is shown in the following example. Note that the group context in the module XLIFF file does not mention the `example_material` module, which is now part of the XLIFF file context.

```
<group resname="example">
  <trans-unit id="anno_0">
    <source>Example material</source>
    <target>Exemple de matériel</target>
    <note>Description for example_material::example</note>
  </trans-unit>
</group>
```

26.3.4   Translation lookup order

When an annotation text in a certain module needs to be translated, the corresponding XLIFF file is looked for in this order:

1. The module XLIFF file for the module,

2. the package XLIFF file for the modules package, and

3. the package XLIFF file for any of the modules package parents up to MDL search path root.

In the following example with a module `::parent::m`:

```
<search-path-root>
  +--- parent
       +--- m.mdl
```

```
        +--- m_fr.xlf      // first lookup
        +--- fr.xlf        // second lookup
    +--- fr.xlf            // third lookup
```

the translation of an annotation from `m.mdl` will be looked up in:

1. `parent/m_fr.xlf` (context: `::parent::m`)

2. `parent/fr.xlf` (context: `::parent`)

3. `fr.xlf` (context empty)

Note: A function variant (Section 12.7) or material variant (Section 13.6) has no place to define own annotations on parameters. Their parameters are defined by the function or material definition on which this variant is based on. This implies that the respective module for parameter translations of annotations is not the module of a variant definition, but the module of the non-variant definition for those parameters.

27 Appendix F – Search paths

The system and user paths specified below are recommended to facilitate the interoperation of multiple applications sharing MDL content.

The user paths should precede the system paths in the MDL search path.

27.1 User paths

The default MDL user path is

- `%DOCUMENTS%\mdl`[1]   (on Windows),
- `$HOME/Documents/mdl`   (on Linux), and
- `$HOME/Documents/mdl`   (on Mac OS).

The MDL user path can be changed via the environment variable `MDL_USER_PATH`. The environment variable can contain multiple paths which are separated by semicolons (on Windows) or colons (on Linux and Mac OS), respectively.

27.2 System paths

The default MDL system path is

- `%PROGRAMDATA%\NVIDIA Corporation\mdl`   (on Windows),
- `/opt/nvidia/mdl`   (on Linux), and
- `/Library/Application Support/NVIDIA Corporation/mdl`   (on Mac OS).

The MDL system path can be changed via the environment variable `MDL_SYSTEM_PATH`. The environment variable can contain multiple paths which are separated by semicolons (on Windows) or colons (on Linux and Mac OS), respectively.

---

[1]The placeholder `%DOCUMENTS%` refers to the standard folder identified by `FOLDERID_Documents` from the Windows API (usually `%USERPROFILE%\Documents`).

28 Appendix G – External bindings

The main part of the MDL Specification defines how elements in MDL source code are named and referenced within the source code itself. This appendix provides definitions for binding MDL elements with external formats and systems. The exact bindings to specific formats and systems is left to separate documents which may reference the definitions in this appendix.

The following sections define

- and how MDL functions with user-defined structure return types can be mapped to nodes with multiple output ports in node graph systems.

28.1 Binding MDL functions to nodes with multiple output ports

In MDL, functions can only return results in their return value. Multiple results can be returned in compound types, where user-defined structures (Section 8) are the generic solution.

Node graph representations, such as UsdShade or MaterialX, allow multiple *output ports* for a node. Binding an MDL function that has a user-defined structure type as return type to a node has several choices, which are detailed in this binding definition. In particular, user-defined structures have also a use as abstraction in MDL and should then be offered as a single port on a shade node.

The binding definition consists of two parts, one for each direction: The binding from a node to an MDL function defines a conflict-free mapping from output ports to MDL function return values, and the reverse direction from MDL to a node defines an annotation to indicate which output ports should be generated by default.

28.1.1 Mapping nodes to MDL functions

Given a shade graph node with one or more output ports and an MDL function bound to this node as implementation, the following rules in the given order define an unambiguous map between the output port names and the functions return value:

1. If an output port is named `out`, it maps to the full return value.

2. If an output port is named the same as a field name of a structure-type return value, it maps to this field value.

3. If the node has only one output port and the MDL function's return type is not a user-defined structure, the output port maps to the full return value.

4. Otherwise, the mapping of this output port is ill-defined and an error.

Note 1: `out` is a reserved name in MDL, while it is the default name for single output ports in MaterialX.

Note 2: Only the first level of structure fields is addressable with this mapping. If the return type structure contains another structure type, its nested fields cannot be bound to output ports.

28.1.2 Mapping MDL functions to nodes

Given an MDL function, there are several ways of setting up the output ports to make a node compliant with the mapping defined in the previous Section 28.1.1, which defines the eligible port names and their mapping but not which ones are really created and offered to a user as an initial default configuration of a node.

There are three main choices:

1. Only one output port named `out` bound to the full value.

2. Output ports for all fields named like the field names.

3. Both combined, i.e., one output port named out for the full value and output ports for all fields.

The standard `anno::node_output_port_default` annotation (Section 18) can be used on a user-defined structure definition or on the return type of a function definition to indicate the preference for one of these three choices. These choices are defined in a respective enumeration in the standard annotation module:

```
enum anno::node_port_mode {
    node_port_value_only,
    node_port_fields_only,
    node_port_value_and_fields
};
```

The default is `node_port_value_only`.

Note 1: A system may allow modifications of the available ports or ignore the recommendation here altogether.

Note 2: In addition, individual fields from the structure-type return value can be ignored in this mapping by using the standard `anno::hidden` annotation on the fields.

29 Appendix H – Material definition normal form

This appendix specifies how material expressions can be transformed in a meaning-preserving way. The transformations defined here are intended to make use of properties of certain MDL constructs (e.g. conditional expressions, distribution function properties) to simplify the translation and analysis of materials.

The process of transformation according to the rules in this appendix is called *normalization*. The *normal form* of an expression is found by repeated transformations, until no rule can be applied anymore.

For the purpose of this appendix, a simplified representation of materials is used. A material definition consists of the material's signature (return type, name and parameters) and an expression e of type `material`:

$$\texttt{material}\, f(t_1\, p_1, \ldots, t_n\, p_n) = e \quad \text{(material definition)}$$

Section 29.1 introduces the simplified material expression language in which the normalization rules are defined, Section 29.2 defines how MDL material definitions map to this simplified material expressions, and Section 29.3 specifies the transformation rules.

Definitions

The following definitions are used in the rest of this appendix:

1. We use *type(e)* to describe the type of the expression e.

2. Transformation rules have one of the following forms:

Form	Meaning
$e_1 \longrightarrow e_2$	Expression e_1 can be transformed to e_2.
$\frac{c_1 \ldots c_n}{e_1 \longrightarrow e_2}$	Expression e_1 can be transformed to e_2 if the conditions $c_1 \ldots c_n$ are met.

29.1 Material term syntax

The syntax of a material term e is defined by the following grammar:

$$
\begin{array}{rcll}
e & : & f(e, \ldots, e) & \text{function call} \\
  & | & p & \text{parameter} \\
  & | & l & \text{literal} \\
f, p & : & \textit{identifier} & \text{function and parameter names}
\end{array}
$$

Note: value construction and type conversion are expressed as function calls in this language.

29.2 Mapping MDL to material terms

Material expressions in MDL are more complex than the syntax above allows. The following transformations have to be applied to MDL material expressions before the rules in the next section are applied.

1. Array indexing, structure selection and conditional expressions as applications are replaced by function calls:

    (a) $e_1[e_2] \longrightarrow \texttt{index}_{t[\,]}(e_1, e_2)$ where t is the type of the array elements.

    (b) $e.n \longrightarrow \texttt{select}_{s,n}(e)$ where s is the structure type of e.

    (c) $e_1 \,?\, e_2 : e_3 \longrightarrow \texttt{cond}_t(e_1, e_2, e_3)$ where t is the type of the conditional.

2. All let-bound variables, named constants or material definitions, i.e., functions returning a material, are replaced by their definitions (inlining). Let expressions are eliminated after their declared variables have been inlined.

3. All implicit type conversions are made explicit using conversion functions.

29.3   Rules

The rules defined in this section have to be applied to all material definitions until no further rule applications are possible. The resulting terms are in normal form.

29.3.1   General rules

The general rules in this section describe overall rule application to material terms.

The rule *declarative call* defines how rules are applied to sub-expressions of call expressions.

$$\frac{e \longrightarrow e'}{f(\ldots,e,\ldots) \longrightarrow f(\ldots,e',\ldots)} \quad \text{(declarative call)}$$

MDL allows conditional expressions on materials. The rule *conditional propagation* defines how a conditional expression can propagate down the material term until it is applied either to DFs or to material inputs.

$$\begin{array}{c} t_i = type(e_{1i}) \\ t \in \{ \quad \texttt{material}, \texttt{material\_surface}, \texttt{material\_volume}, \\ \texttt{material\_emission}, \texttt{material\_geometry} \quad \} \\ \hline \mathsf{cond}_t(e_c, f(e_{11},\ldots,e_{1n}), f(e_{21},\ldots,e_{2n})) \longrightarrow \\ f(\mathsf{cond}_{t_1}(e_c, e_{11}, e_{21}), \ldots, \mathsf{cond}_{t_n}(e_c, e_{1n}, e_{2n})) \end{array} \quad \text{(conditional propagation)}$$

29.3.2   Thin-film elimination

These rules define where the `thin_film` modifier has no effect and can be eliminated.

Definitions

1. *non_thin_film_bsdfs* = { `bsdf`, `diffuse_reflection_bsdf`, `diffuse_transmission_bsdf`, `specular_bsdf`, `measured_bsdf`, `sheen_bsdf`, `ward_geisler_moroder_bsdf` } are the BSDFs on which `thin_film` does not have an effect.

Rules

$$\texttt{thin\_film}(a_1, b_1, \texttt{thin\_film}(a_2, b_2, e)) \longrightarrow \texttt{thin\_film}(a_2, b_2, e) \quad \text{(nested thin-film)}$$

$$\frac{f \in \textit{non\_thin\_film\_bsdfs}}{\texttt{thin\_film}(\ldots, f(\ldots)) \longrightarrow f(\ldots)} \quad \text{(non-thin-film)}$$

29.3.3   Thin-film propagation

These rules define where the `thin_film` modifier propagates down in the BSDF tree.

Definitions

1. *mixers* = { `normalized_mix`, `color_normalized_mix`, `clamped_mix`, `color_clamped_mix`, `unbounded_mix`, `color_unbounded_mix` } is the set of mixing BSDF combiners.

2. *layerers* = { weighted_layer, color_weighted_layer, measured_curve_layer, color_measured_curve_layer } is the set of BSDF layerers.

3. *measured_factors* = { measured_factor, measured_curve_factor } is the set of measured factor modifiers.

Rules

$$\texttt{thin\_film}(\ldots, \texttt{tint}(\ldots, e)) \longrightarrow \texttt{tint}(\ldots, \texttt{thin\_film}(\ldots, e)) \quad \text{(tint)}$$

$$\frac{\begin{array}{c} \textit{mix} \in \textit{mixers} \\ s = \texttt{bsdf\_component} \end{array}}{\begin{array}{c} \texttt{thin\_film}(\ldots, \textit{mix}(s[\,](s(w_1, e_1), \ldots, s(w_n, e_n)))) \longrightarrow \\ \textit{mix}(s[\,](s(w_1, \texttt{thin\_film}(\ldots, e_1)), \ldots, s(w_n, \texttt{thin\_film}(\ldots, e_n)))) \end{array}} \quad \text{(mixers)}$$

$$\frac{\begin{array}{c} \text{for all parameters of } f : \textit{type}(e_i) = \texttt{bsdf} \\ f \in \textit{layerers} \end{array}}{\texttt{thin\_film}(\ldots, f(\ldots, e_i, \ldots)) \longrightarrow f(\ldots, \texttt{thin\_film}(\ldots, e_i), \ldots)} \quad \text{(layerers)}$$

$$\frac{f \in \textit{measured\_factors}}{\texttt{thin\_film}(\ldots, f(\ldots, e)) \longrightarrow f(\ldots, \texttt{thin\_film}(\ldots, e))} \quad \text{(measured factors)}$$

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NVIDIA Material Definition Language 1.8.2

30 Changes to this document

Main changes for MDL 1.8 since the MDL specification document version 1.7.2 from January 17, 2022.

30.1 Changes for version 1.8.2

- Removed the draft status of this document.
- Removed meaningless references to a preprocessor. (Page 15)
- Clarified that MDL comments can be nested. (Page 15)
- Extend list of separators in MDL and clarify their purpose. (Page 17)
- Clarified that *unicode identifiers* cannot be empty. (Page 17)
- Fixed the accidentally dropped grammar production rule for the import statements in MDL files. (Pages 13, 83, and 139)
- Clarified that let-bound variables cannot be used in their own initializer expressions. (Pages 67 and 75)
- Added a reference to the approximation used for the Mie scattering model of `fog_vdf`. (Page 126)
- Clarified that the `particle_size` parameter of the new `fog_vdf` approximative Mie VDF model refers to the particle diameter. (Page 126)

30.2 Changes for version 1.8.1

- Updated version to 1.8.
- Reduced the requirement on thin-walled materials that they *should* have equal transmission from both sides. (Pages 1, 69, and 70)
- Added part to supported selector string components for OpenEXR. (Page 6)
- Added the operator function call to the precedence table of all operators. (Page 16)
- Added the cast operator to the precedence table of all operators. (Page 16)
- Moved `operator` from the set of words reserved for future use to the reserved words in use. (Page 18)
- Added section for *unicode identifiers*. (Page 17)
- Renamed Section 21 to include values. (Page 21)
- Clarified in Section 22 on variables that their use in let-expressions is read-only. (Page 22)
- Clarified that binary logical operators may or may not use short-circuit evaluation. (Page 25)
- Added definition of lvalues and rvalues. (Page 25)
- Removed redundant subsections that `light_profile` and `bsdf_measurement` have no members. (Pages 40 and 41)
- Added requirement to check for array out-of-bounds access and to return default-constructed values in this case. (Page 45)
- Clarified that function parameters are lvalues in their procedural implementation bodies. (Page 59)
- Added that function parameters can only be used as read-only rvalues in functions defined by an expression. (Page 65)
- Added that function parameters can only be used as read-only rvalues in let-expression. (Page 67)
- Changed the grammar for the let-expression from *unary_expression* to *assignment_expressions* for the expression affected by the variables. This ensures the right scope precedence, e.g., the let-expression ends at a sequence operator. (Pages 67 and 75)
- Removed using alias declarations. They are replaced by Unicode identifiers directly supported as package and module names. (Page 81)

- Added operator function call syntax for all applicable operators. (Page 68)

- Clarified that material parameters can only be used as read-only rvalues in material definitions. (Page 73)

- Clarified that material parameters can only be used as read-only rvalues in let-expression. (Page 75)

- Removed the support for annotations on packages with the `package.pkg` file. (Pages 79 and 81)

- Added Unicode identifiers for package and module names. (Pages 81 and 17)

- Changed productions for *import_path*, *qualified_import* to allow Unicode identifiers in package and module names. (Page 81)

- Added a `collapsed` parameter to the `anno::in_group` standard annotation to control the UI presentation of groups. (Page 92)

- Added the standard annotation `node_output_port_default` and the respective enumeration type `node_port_mode` to control the default initialization of output ports for external shade graph nodes when they are created for MDL functions. (Page 96)

- Added the standard annotation `native` to hint that a function or material might have a native implementation in the integration. (Page 96)

- Added the standard annotation `noinline` to hint that a function or material should not be inlined by the compiler. (Page 96)

- Added that texture spaces and their respective tangents return in volume shading their respective values at the surface entry point of the current light-transport path. (Page 98)

- Added that `state::texture_space` and the related tangent state functions return the zero vector in case the index is out of the range of available texture spaces. (Page 97)

- Clarified the exact interpolation curve for `math::smoothstep` and that it is undefined for a zero or reversed interpolation range. (Page 107)

- Added `float4x4` as supported data type for scene data lookup. (Page 112)

- Removed the requirement on the scene data lookup functions to provide literal strings as arguments for the scene data names. They are now uniform strings and can be connected to uniform string parameters of a material of function definition. (Page 112)

- Added a diffuse reflection BSDF modeling spherical Lambertian scatterers. (Page 116)

- Added an approximative Mie VDF model for fog and cloud-like media. (Page 126)

- Added `custom_curve_layer`, `color_custom_curve_layer` and `directional_factor` as eligible base BSDF for the `thin_film` BSDF modifier. (Page 128)

- Clarified that the `measured_factor` modifier BSDF allows reflectivities above one and it is in the responsibility of a material author to ensure energy conservation. (Page 130)

- Added optional trailing commas to the productions of *parameter_list*, *argument_list*, *enum_type_declaration* and *annotation_block*. (Pages 59, 59, 51 and 79)

- Added a new Appendix G on external bindings. (Page 163)

- Added a section in Appendix G for the recommended binding of MDL functions to nodes with multiple output ports. (Page 163)