

Preprocessor embed - Binary Resource Inclusion

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Abstract:

Pulling binary data into a program often involves external tools and build system coordination. Many programs need binary data such as images, encoded text, icons and other data in a specific format. Current state of the art for working with such static data in C includes creating files which contain solely string literals, directly invoking the linker to create data blobs to access through carefully named extern variables, or generating large brace-delimited lists of integers to place into arrays. As binary data has grown larger, these approaches have begun to have drawbacks and issues scaling. From parsing 5 megabytes worth of integer literal expressions into AST nodes to arbitrary string literal length limits in compilers, portably putting binary data in a C program has become an arduous task that taxes build infrastructure and compilation memory and time.

This proposal provides a flexible preprocessor directive for making this data available to the user in a straightforward manner.

1 Introduction

For well over 40 years, people have been trying to plant data into executables for varying reasons. Whether it is to provide a base image with which to flash hardware in a hard reset, icons that get packaged with an application, or scripts that are intrinsically tied to the program at compilation time, there has always been a strong need to couple and ship binary data with an application.

C does not make this easy for users to do, resulting in many individuals reaching for utilities such as `xxd`, writing python scripts, or engaging in highly platform-specific linker calls to set up `extern` variables pointing at their data. Each of these approaches come with benefits and drawbacks. For example, while working with the linker directly allows injection of vary large amounts of data (5 MB and upwards), it does not allow accessing that data at any other point except runtime. Conversely, Doing all of these things portably across systems and additionally maintaining the dependencies of all these resources and files in build systems both like and unlike `make` is a tedious task.

Thusly, we propose a new preprocessor directive whose sole purpose is to be `#include`, but for binary data: `#embed`.

1.1 Motivation

The reason this needs a new language feature is simple: current source-level encodings of “producing binary” to the compiler are incredibly inefficient both ergonomically and mechanically. Creating a brace-delimited list of numerics in C comes with baggage in the form of how numbers and lists are formatted. C’s preprocessor and the forcing of tokenization also forces an unavoidable cost to lexer and parser handling of values.

Therefore, using arrays with specific initialized values of any significant size becomes borderline impossible. One would [think this old problem](#) would be work-around-able in a succinct manner. Given how old this desire is (that `comp.std.c` thread is not even the oldest recorded feature request), proper solutions would have arisen. Unfortunately, that could not be farther from the truth. Even the compilers themselves suffer build time and memory usage degradation, as contributors to the LLVM compiler ran the gamut of [the biggest problems that motivate this proposal](#) in a matter of a week or two earlier this very year. Luke is not alone in his frustrations: developers all over suffer from the inability to include binary in their program quickly and perform [exceptional gymnastics](#) to get around the compiler’s inability to handle these cases.

C developer progress is impeded regarding the [inability to handle this use case](#), and it leaves both old and new programmers wanting.

1.2 But *How* Expensive Is This?

Many different options as opposed to this proposal were seriously evaluated. Implementations were attempted in at least 2 production-use compilers, and more in private. To give an idea of usage and size, here are results for various compilers on a machine with the following specification:

- Intel Core i7 @ 2.60 GHz
- 24.0 GB RAM
- Debian Sid or Windows 10
- Method: Execute command hundreds of times, stare extremely hard at `htop`/Task Manager

While `time` and `Measure-Command` work well for getting accurate timing information and can be run several times in a loop to produce a good average value, tracking memory consumption without intrusive efforts was much harder and thusly relied on OS reporting with fixed-interval probes. Memory usage is therefore approximate and may not represent the actual maximum of consumed memory. All of these are using the latest compiler built from source if available, or the latest technology preview if available. Optimizations at `-O2` (GCC & Clang style)/`/O2 /Ob2` (MSVC style) or equivalent were employed to generate the final executable.

1.2.1 Speed Size

Strategy	40 kilobytes	400 kilobytes	4 megabytes	40 megabytes
#embed GCC	0.236 s	0.231 s	0.300 s	1.069 s
xxd-generated GCC	0.406 s	2.135 s	23.567 s	225.290 s
xxd-generated Clang	0.366 s	1.063 s	8.309 s	83.250 s
xxd-generated MSVC	0.552 s	3.806 s	52.397 s	Out of Memory

1.2.2 Memory Size

Strategy	40 kilobytes	400 kilobytes	4 megabytes	40 megabytes
#embed GCC	17.26 MB	17.96 MB	53.42 MB	341.72 MB
xxd-generated GCC	24.85 MB	134.34 MB	1,347.00 MB	12,622.00 MB
xxd-generated Clang	41.83 MB	103.76 MB	718.00 MB	7,116.00 MB
xxd-generated MSVC	~48.60 MB	~477.30 MB	~5,280.00 MB	Out of Memory

1.2.3 Analysis

The numbers here are not particularly reassuring. Furthermore, privately owned compilers and other static analysis tools perform almost exponentially poorly here, taking vastly more memory and thrashing CPUs to 100% for several minutes (to sometimes several hours if e.g. the Swap is engaged due to lack of main memory). Every compiler must always consume a certain amount of memory in a relationship directly linear to the number of tokens produced. After that, it is largely implementation-dependent what happens to the data.

The GNU Compiler Collection (GCC) uses a tree representation and has many places where it spawns extra “garbage”, as its called in the various bug reports and work items from implementers. There has been a 16+ year effort on the part of GCC to reduce its memory usage and speed up initializers ([C Bug Report](#) and [C++ Bug Report](#)). Significant improvements have been made and there is plenty of room for GCC to improve here with respect to compiler and memory size. Somewhat unfortunately, one of the current changes in flight for GCC is the removal of all location information beyond the 256th initializer of large arrays in order to save on space. This technique is not viable for static analysis compilers that promise to recreate source code exactly as was written, and therefore discarding location or token information for large initializers is not a viable cross-implementation strategy.

LLVM’s Clang, on the other hand, is much more optimized. They maintain a much better scaling and ratio but still suffer the pain of their token overhead and Abstract Syntax Tree representation, though to a much lesser degree than GCC. A bug report was filed but talk from two prominent LLVM/Clang developers made it clear that optimizing things any further would [require an extremely large refactor and functionality add of parser internals](#), with potentially dubious gains. As part of this proposal, the implementation provided does

attempt to do some of these optimizations, and follows some of the work done in [this post](#) to try and prove memory and file size savings. (The savings in trying to optimize parsing large array literals were “around 10%”, compared to the order-of-magnitude gains from `#embed` and similar techniques).

Microsoft Visual C (MSVC) scales the worst of all the compilers, even when given the benefit of being on its native operating system. Both Clang and GCC outperform MSVC on Windows 10 or WINE as of the time of writing.

Linker tricks on all platforms perform better with time (though slower than `#embed` implementation), but force the data to be optimizer-opaque (even on the most aggressive “Link Time Optimization” or “Whole Program Optimization” modes compilers had). Linker tricks are also exceptionally non-portable: whether it is the `incbin` assembly command supported by certain compilers, specific invocations of `rc.exe/objcopy` or others, non-portability plagues their usefulness in writing Cross-Platform C (see Appendix for listing of techniques). This makes C decidedly unlike the “portable assembler” advertised by its proponents (and my Professors and co-workers).

2 Design

There are two design goals at play here, sculpted to specifically cover industry standard practices with build systems and C programs. The first is to enable developers to get binary content quickly and easily into their applications. This can be icons/images, scripts, tiny sound effects, hardcoded firmware binaries, and more. In order to support this use case, this feature was designed for simplicity and builds upon widespread existing practice.

2.1 First Principle: Simplicity and Familiarity

Providing a directive that mirrors `#include` makes it natural and easy to understand and use this new directive. It accepts both chevron-delimited (`<>`) and quote-delimited (`" "`) strings like `#include` does. This matches the way people have been generating files to `#include` in their programs, libraries and applications: matching the semantics here preserves the same mental model. This makes it easy to teach and use, since it follows the same principles:

```
#include <limits.h>

/* default is unsigned char */
const unsigned char icon_display_data[] = {
    #embed "art.png"
};

/* specify a type-name to change array type */
const char reset_blob[] = {
    #embed char "data.bin"
};
```

Because of its design, it also lends itself to being usable in a wide variety of contexts and with a wide variety of vendor extensions. For example:

```
#include <limits.h>

/* attributes work just as well */
const signed char aligned_data_str[] __attribute__((aligned (8))) = {
    #embed signed char "attributes.xml"
```

```
};
```

The above code obeys the alignment requirements for an implementation that understands GCC directives, without needing to add special support in the `#embed` directive for it: it is just another array initializer, like everything else.

2.1.1 Type Flexibility

As hinted at in previous sections's code snippets, a type can be specified after the `#embed` to view the data in a very specific manner. This allows data to be initialized as exactly that type.

```
#include <limits.h>

/* specify a type-name to change array type */
const int shorten_flac[] = {
    #embed int "stripped_music.flac"
};
```

The contents of the resource are mapped in an implementation-defined manner to the data, such that it will use `sizeof(type-name) * CHAR_BIT` bits for each element. If the file does not have enough bits to fill out a multiple of `sizeof(type-name) * CHAR_BIT` bits, then a diagnostic is required. Furthermore, we require that the type passed to `#embed` must be one of the following fundamental types, signed or unsigned, spelled exactly in this manner:

- char, unsigned char, signed char
- short, unsigned short, signed short
- long, unsigned long, signed long
- long long, unsigned long long, signed long long

More types can be supported by the implementation if the implementation so chooses (both the GCC and Clang prototypes described below support more than this). The reason exactly these types are required is because these are the only types for which there is a suitable way to obtain their size at pre-processor time. Quoting from §5.2.4.2.1, paragraph 1:

The values given below shall be replaced by constant expressions suitable for use in `#if` preprocessing directives.

This means that the types above have a specific size that can be properly initialized by a preprocessor entirely independent of a proper C frontend, without needing to know more than how to be a preprocessor. This does require that every use of `#embed` is accompanied by a `#include <limits.h>` (or, in the case of C++, `#include <climits>`).

2.1.2 Existing Practice - Search Paths

It follows the same implementation experience guidelines as `#include` by leaving the search paths implementation defined, with the understanding that implementations are not monsters and will generally provide `-fembed-path/-fembed-path=` and other related flags as their users require for their systems. This gives implementers the space they need to serve the needs of their constituency.

2.1.3 Existing Practice - Discoverable and Distributable

Build systems today understand the make dependency format, typically through use of the compiler flags

-(M)MD and friends. This sees widespread support, from CMake, Meson and Bazel to ninja and make. Even VC++ has a version of this flag - /showIncludes - that gets parsed by build systems.

This preprocessor directive fits perfectly into existing build architecture by being discoverable in the same way with the same tooling formats. It also blends perfectly with existing distributed build systems which preprocess their files with -frewrite-includes before sending it up to the build farm, as distcc and icecc do.

2.2 Second Principle: Efficiency

The second principle guiding the design of this feature is facing the increasing problems with #include and typical source-style rewriting of binary data. Array literals do not scale. Processing large comma-delimited, *brace-init-lists* of data-as-numbers produces excessive compilation times. Compiler memory usage reaches extraordinary levels that are often ten to twenty times (or more) of the original desired data file (see above tables in the Motivation section). Part of this is endemic to the compiler: the preprocessor demands that tokens be

String literals do not suffer the same compilation times or memory scaling issues, but the C Standard has limits on the maximum size of string literals (§5.2.4.1, “— 4095 characters in a string literal (after concatenation)”). One implementation takes the C Standard quite almost exactly at face value: it allows 4095 bytes in a single string *piece*, so multiple quoted pieces each no larger than 4095 bytes must be used to create large enough string literals to handle the work.

#embed’s specification is such that it behaves “as if” it expands to a brace-delimited, comma-separated sequence of integral literals. This means an implementation does not have to run the full gamut of producing an abstract syntax tree of an expression. It does not need a fully generic expression list that spans several AST nodes for what is logically just a sequence of numeric literals. A more direct representation can be used internally in the compiler, drastically speeding up processing and embedding of the binary data into the translation unit for use by the program. One of the test implementations uses such a direct representation and achieves drastically reduced memory and compile time footprint, making large binary data accessible in C programs in an affordable manner.

2.2.1 Infinity Files

The earliest adopters and testers of the implementation reported problems when trying to access POSIX-style char devices and pseudo-files that do not have a logical limitation. These “infinity files” served as the motivation for introducing the “limit” parameter; there are a number of resources which are logically infinite and thusly having a compiler read all of the data would result an Out of Memory error, much like with #include if someone did #include "/dev/urandom".

The limit parameter is specified before the resource name in #embed, like so:

```
const int please_dont_oom_kill_me[] = {  
    #embed int 32 "/dev/urandom"  
};
```

This prevents locking compilers in an infinite loop of reading from potentially limitless resources. Note the parameter is a hard upper bound, and not an exact requirement. A resource may expand to 16 elements and not the maximum of 32.

3 Implementation Experience

An implementation of this functionality is available in branches of both GCC and Clang, accessible right now with an internet connection through the online utility Compiler Explorer. The Clang compiler with this functionality is called [“x86-64 clang \(std::embed\)”](#) and the GCC compiler is called [“x86-64 gcc \(std::embed\)”](#) in the Compiler Explorer UI.

4 Alternative Syntax

There has been concerns expressed about the form of this feature – whether or not it could be a preprocessor directive itself, or a magical macro introduced in the language, or a special pragma. Each of these has their own specific syntax tradeoffs. The primary choice and the one advocated for is the syntax as shown above: a plain preprocessor directive analogous to `#include`. It is written as `#embed`, but other names (previously recommended by the Community) are `#include_bin`, `#include_binary`, `#incbin`, or `#load_binary`.

The syntax can also be adjusted. A preprocessor directive is preferred because that allows it to be findable by the end of Preprocessor.

5 Wording - C


This wording is relative to C's latest working draft.

5.1 Intent

The intent of the wording is to provide a preprocessing directive that:

- takes a string literal identifier – potentially from the expansion of a macro – and uses it to find a unique resource on the command line;
- if embedding one of the integer types, then it behaves as if it produces a list of values suitable for the initialization of an array as well as initializes each element according to the specific environment limits found in `<limits.h>`;
- if not embedding one of the integer types, allows an implementation issue a diagnostic that the tool or implementation cannot handle such a type, while giving other implementations the freedom to support said type through implementation defined behavior;
- errors if the size of the resource does not have enough bits to fully and properly initialize all the values generated by the directive;
- allows a limit parameter limiting the number of elements to be specified;
- and, present such contents as if by a list of values, such that it can be used to initialize arrays of known and unknown bound even if additional elements of the whole initialization list come before or after the directive.

5.2 Proposed Language Wording

Note: The  is a stand-in character to be replaced by the editor.

Add another *control-line* production and a new *parenthesized-non-header* to §6.10 Preprocessing Directives, Syntax, paragraph 1:

control-line:

...
embed *pp-tokens new-line*

parenthesized-non-header:

(_{opt} pp-tokens)_{opt}

Add a new sub clause as §6.10.❖ to §6.10 Preprocessing Directives, preferably after §6.10.2 Source file inclusion:

§6.10.❖ Resource embedding

Constraints

¹A `#embed` directive shall identify a resource that can be processed by the implementation as a binary data sequence, of an optionally specified type, that results in a part of or a whole of an *initializer-list*.

Semantics

² A preprocessing directive of the form

`# embed parenthesized-non-headeropt digit-sequenceopt < h-char-sequence > new-line`

searches a sequence of implementation-defined places for a resource identified uniquely by the specified sequence between the < and >. The named resource is searched for in an implementation-defined manner.

³ A preprocessing directive of the form

`# embed parenthesized-non-headeropt digit-sequenceopt " q-char-sequence " new-line`

searches a sequence of implementation-defined places for a resource identified uniquely by the specified sequence between the ", or < and >, delimiters. The named resource is searched for in an implementation-defined manner. If this search is not supported, or if the search fails, the directive is reprocessed as if it read

`# embed parenthesized-non-headeropt digit-sequenceopt < h-char-sequence > new-line`

with the identical contained *q-char-sequence* (including > characters, if any) from the original directive.

⁴ If a *parenthesized-non-header* is not specified, then the directive behaves as if the tokens of the *parenthesized-non-header* are `unsigned char`. If a *parenthesized-non-header* is specified, outer parentheses must be present if it contains one or more of `"`, `<` or `>`.

⁵ If either form of the `#embed` directive specified is not preceded by an `#include` directive for `<limits.h>`, then an implementation may issue a diagnostic.

⁶ Let the *parenthesized-non-header* tokens be `T`. Either form of the `#embed` directive specified previously, for the following token sequences of `T`, behave as if it were expanded to an *initializer-list*. Specifically, each element of the *initializer-list* behaves as if characters from the resource were read into an array of `unsigned char` and the array was overlaid into a `T` to produce an *integer constant expressions* of exactly `ELEMENT_WIDTH` bits and must have a value between `ELEMENT_MIN` and `ELEMENT_MAX`, inclusive. If the implementation-defined bit size of the resource's contents are not a multiple of the `ELEMENT_WIDTH`, then the implementation shall issue a diagnostic. The values for `ELEMENT_WIDTH`, `ELEMENT_MIN`, and `ELEMENT_MAX` correspond to `T` as follows:

— If `T` is `char`, `CHAR_WIDTH`, and `CHAR_MIN`, and `CHAR_MAX` are the values, respectively.
 — Otherwise, `T` is signed `char`, then `SCHAR_WIDTH`, `SCHAR_MIN` and `SCHAR_MAX` are the values, respectively.
 — Otherwise, `T` is unsigned `char`, then `UCHAR_WIDTH`, `0` and `UCHAR_MAX` are the values, respectively.
 — Otherwise, `T` is short or signed short, then `SHRT_WIDTH`, `SHRT_MIN` and `SHRT_MAX` are the values, respectively.
 — Otherwise, `T` is unsigned short, then `USHRT_WIDTH`, `0` and `USHRT_MAX`, are the values respectively.
 — Otherwise, `T` is long or signed long, then `LONG_WIDTH`, `LONG_MIN` and `LONG_MAX` are the values, respectively.
 — Otherwise, `T` is unsigned long, then `ULONG_WIDTH`, `0` and `ULONG_MAX`, are the values respectively.
 — Otherwise, `T` is long long or signed long long, then `LLONG_WIDTH`, `LLONG_MIN` and `LLONG_MAX` are the values, respectively.
 — Otherwise, `T` is unsigned long long, then `ULLONG_WIDTH`, `0` and `ULLONG_MAX`, are the values respectively.

⁷ Otherwise, if `T` is not one of the above sequence of tokens, then it is implementation-defined whether or not the directive is supported. If it is, it behaves as if it is replaced by an implementation-defined mapping of the contents of the resource into an *initializer-list* suitable for initializing an array of `T`. Specifically, each element of the *initializer-list* behaves as if characters from the resource were read into an array of `unsigned char` with a size `sizeof(T)` and overlaid into the resulting element¹⁸♦. If the implementation-defined bit size of the resource's contents are not a multiple of `sizeof(T) * CHAR_BIT`, then the implementation shall issue a diagnostic.

⁸ If a *digit-sequence* is specified, it shall be an integer constant expression resulting in an unsigned value suitable for use in `#if` preprocessing directives. The mapping from the contents of the resource to the elements of the *initializer-list* shall contain up to *digit-sequence* elements according to the above, and the implementation shall not issue a diagnostic if the implementation-defined bit size is larger than required to produce *digit-sequence* elements.

⁹ If the resulting *initializer-list* is used in a place where a constant expression (6.6) is valid, then the *initializer-list* must be a constant expression. If the resulting *initializer-list* is used as part of the initialization of an array of incomplete type, then the *initializer-list* will contribute to the size of the completed array type at the end of the initializer (6.7.9).

¹⁰ A preprocessing directive of the form

embed *pp-tokens new-line*

(that does not match one of the two previous forms) is permitted. The preprocessing tokens after **embed** in the directive are processed just as in normal text. (Each identifier currently defined as a macro name is replaced by its replacement list of preprocessing tokens.) The directive resulting after all replacements shall match one of the two previous forms¹⁸♦♦. The method by which a sequence of preprocessing tokens between a `<` and a `>` preprocessing token pair or a pair of `"` characters is combined into a single resource name preprocessing token is implementation-defined.

Add 3 new Example paragraphs below the above text in §6.10.♦ Resource embedding:

11 EXAMPLE 1 Placing a small image resource.

```
#include <stddef.h>
#include <limits.h>

void have_you_any_wool(const unsigned char*, size_t);

int main (int, char*[]) {
    const unsigned char baa_baa[] = {
#embed "black_sheep.ico"
    };

    have_you_any_wool(baa_baa,
        sizeof(baa_baa) / sizeof(*baa_baa));

    return 0;
}
```

12 EXAMPLE 2 Checking the first 4 elements of a sound resource.

```
#include <assert.h>
#include <limits.h>

int main (int, char*[]) {
    const char sound_signature[] = {
#embed char 4 <sdk/jump.wav>
    };

    // verify PCM WAV resource
    assert(sound_signature[0] == 'R');
    assert(sound_signature[1] == 'I');
    assert(sound_signature[2] == 'F');
    assert(sound_signature[3] == 'F');
    assert((sizeof(sound_signature) / sizeof(*sound_signature)) ==
        4);

    return 0;
}
```

13 EXAMPLE 3 Diagnostic for resource which is too small.

```
#include <limits.h>

int main (int, char*[]) {
    const unsigned long long coefficients[] = {
#embed unsigned long long "only_16_bits.bin"
    };

    return 0;
}
```

An implementation must produce a diagnostic where 16 bits (i.e., the implementation-defined bit size) is less than `ULLONG_WIDTH`, or the implementation-defined bit size modulo `ULLONG_WIDTH` is not 0. 14 EXAMPLE 4 Extra elements added to array initializer.

```
#include <limits.h>

#include <string.h>
```

```

#ifdef SHADER_TARGET
#define SHADER_TARGET "phong.glsl"
#endif

extern char* null_term_shader_data;

void fill_in_data () {
    const char internal_data[] = {
#ifdef SHADER_TARGET
        , 0 };

    strcpy(null_term_shader_data, internal_data);
}

```

18💎 Note that this is similar to how `fread` (7.21.8.1) behaves, but specifically tailored for the purposes of requiring similar semantics at translation time.

18💎💎 Note that adjacent string literals are not concatenated into a single string literal (see the translation phases in 5.1.1.2); thus, an expansion that results in two string literals is an invalid directive. **Forward references:** macro replacement (6.10.💎).

6 Wording - C++

This wording is relative to C++'s latest working draft.

6.1 Intent

The intent of the wording is to provide a preprocessing directive that:

- takes a string literal identifier – potentially from the expansion of a macro – and uses it to find a unique resource on the command line;
- if embedding one of the integer types, then it behaves as if it produces a list of values suitable for the initialization of an array as well as initializes each element according to the specific environment limits found in `<climits>`;
- if not embedding one of the integer types, allows an implementation issue a diagnostic that the tool or implementation cannot handle such a type, while giving other implementations the freedom to support said type through implementation defined behavior;
- errors if the size of the resource does not have enough bits to fully and properly initialize all the values generated by the directive;
- allows a limit parameter limiting the number of elements to be specified;
- produces a core constant expression that can be used to initialize `constexpr` arrays;
- produces a diagnostic if the contents do not have enough data to fill out the binary representation of *type-name* values;
- and, present such contents as if it is a list of values, such that it can be used to initialize arrays of known and unknown bound even if additional elements of the whole initialization list come before or after the directive.

6.2 Proposed Feature Test Macro

The proposed feature test macro is `__cpp_pp_embed` for the preprocessor functionality.

6.3 Proposed Language Wording

Append to §14.8.1 Predefined macro names [**cpp.predefined**]'s **Table 16** with one additional entry:

Macro name	Value
<code>__cpp_pp_embed</code>	<code>202006L</code>

Add a new *control-line* production to §15.1 Preamble [**cpp.pre**] and a new grammar production:

control-line:

...

`# embed pp-tokens new-line`

...

parenthesized-non-header:

`(opt pp-tokens opt)`

Add a new sub-clause §15.4 Resource inclusion [cpp.res]:

15.4 Resource inclusion [cpp.res]

¹ A `#embed` directive shall identify a resource file that can be processed by the implementation.

² A preprocessing directive of the form

`# embed parenthesized-non-headeropt digit-sequenceopt < h-char-sequence > new-line`

or

`# embed parenthesized-non-headeropt digit-sequenceopt " q-char-sequence " new-line`

searches a sequence of implementation-defined places for a resource identified uniquely by the specified sequence between the < and > or the " and " delimiters. How the places are specified or the resource identified is implementation-defined.

³ If there is no *parenthesized-non-header*, then the directive behaves as if the tokens of the *parenthesized-non-header* are `unsigned char`. If a *parenthesized-non-header* is specified, outer parenthesis must be present if the *pp-tokens* contain one or more of `"`, `<` or `>`.

⁴ If either form of the `#embed` directive specified is not preceded by an `#include` directive for `<limits>`, then an implementation may issue a diagnostic.

⁵ Let the *parenthesized-non-header* tokens be `T`. Either form of the `#embed` directive specified previously, for the following token sequences of `T`, behave as if it were expanded to an *initializer-list*. Specifically, each element of the *initializer-list* behaves as if characters from the resource were read into an array of `unsigned char` and the array was overlaid into a `T` to produce an *integer constant expressions* of exactly `ELEMENT_WIDTH` bits and must have a value between `ELEMENT_MIN` and `ELEMENT_MAX`, inclusive. If the implementation-defined bit size of the resource's contents are not a multiple of the `ELEMENT_WIDTH`, then the implementation shall issue a diagnostic. The values for `ELEMENT_WIDTH`, `ELEMENT_MIN`, and `ELEMENT_MAX` correspond to `T` as follows:

- If `T` is `char`, `CHAR_WIDTH`, and `CHAR_MIN`, and `CHAR_MAX` are the values, respectively.
- Otherwise, `T` is `signed char`, then `SCHAR_WIDTH`, `SCHAR_MIN` and `SCHAR_MAX` are the values, respectively.
- Otherwise, `T` is `unsigned char`, then `UCHAR_WIDTH`, `0` and `UCHAR_MAX` are the values, respectively.
- Otherwise, `T` is `short` or `signed short`, then `SHRT_WIDTH`, `SHRT_MIN` and `SHRT_MAX` are the values, respectively.
- Otherwise, `T` is `unsigned short`, then `USHRT_WIDTH`, `0` and `USHRT_MAX`, are the values respectively.
- Otherwise, `T` is `long` or `signed long`, then `LONG_WIDTH`, `LONG_MIN` and `LONG_MAX` are the values, respectively.
- Otherwise, `T` is `unsigned long`, then `ULONG_WIDTH`, `0` and `ULONG_MAX`, are the values respectively.
- Otherwise, `T` is `long long` or `signed long long`, then `LLONG_WIDTH`, `LLONG_MIN` and `LLONG_MAX` are the values, respectively.
- Otherwise, `T` is `unsigned long long`, then `ULLONG_WIDTH`, `0` and `ULLONG_MAX`, are the

values respectively.

⁶ Otherwise, if `T` is not one of the above sequence of tokens, then it is implementation-defined whether or not the directive is supported. If it is, then the *initializer-list* represents an implementation-defined mapping from the contents of the resource to the elements of the *initializer-list*. If the implementation-defined bit size of the resource's contents are not a multiple of `sizeof(T) * CHAR_BIT` or `T` does not denote a trivial type (6.8 [basic.types]), then the program is ill-formed.

⁷ If a *digit-sequence* is specified, it shall be an unsigned *integer-literal* and the *initializer-list* will have up to *digit-sequence* elements.

[Example:

```
#include <cstdint>
#include <climits>

void have_you_any_wool(const unsigned char*, std::size_t);

int main (int, char*[]) {
    constexpr const unsigned char baa_baa[] = {
#embed "black_sheep.ico"
    };

    have_you_any_wool(baa_baa,
        sizeof(baa_baa) / sizeof(*baa_baa));

    return 0;
}
```

– end Example]

[Example:

```
#include <cassert>

int main (int, char*[]) {
    constexpr const char sound_signature[] = {
#embed char 4 <sdk/jump.wav>
    };

    // verify PCM WAV resource
    assert(sound_signature[0] == 'R');
    assert(sound_signature[1] == 'I');
    assert(sound_signature[2] == 'F');
    assert(sound_signature[3] == 'F');
    assert((sizeof(sound_signature) / sizeof(*sound_signature)) == 4);

    return 0;
}
```

– end Example]

[Example:

```
#include <climits>
```

```

int main (int, char*[]) {
    const unsigned long long coefficients[] = {
// may produce diagnostic: 16 bits (i.e., implementation-defined bit size)
// is not enough for an unsigned long long (e.g. ULLONG_WIDTH)
#embed unsigned long long "only_16_bits.bin"
    };

    const unsigned char byte_factors[] = {
// may produce diagnostic: 13 bits % UCHAR_WIDTH may not be 0
#embed "13_bits.bin"
    };

    return 0;
}

```

–end Example]

[Example:

```

struct non_trivial {
    non_trivial(int);
};

int main (int, char*[]) {
    const non_trivial nt_arr[] = {
// implementation-defined if supported. if it is,
// diagnostic required as non_trivial is not a trivial type
#embed non_trivial "only_16_bits.bin"
    };

    return 0;
}

```

–end Example]

[Example:

```

#include <algorithm>
#include <iterator>

#ifdef SHADER_TARGET
#define SHADER_TARGET "phong.glsl"
#endif

extern char* null_term_shader_data;

void get_data () {
    constexpr const char internal_data[] = {
#embed char SHADER_TARGET
    , 0 }; // additional element to null terminate content

    std::copy_n(internal_data, std::size(internal_data),
        null_term_shader_data);
}

```

–end Example]

7 Acknowledgements

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8 Appendix

8.1 Existing Tools

This section categorizes some of the platform-specific techniques used to work with C++ and some of the challenges they face. Other techniques used include pre-processing data, link-time based tooling, and assembly-time runtime loading. They are detailed below, for a complete picture of today's landscape of options. They include both C and C++ options.

8.1.1 Pre-Processing Tools

1. Run the tool over the data (`xxd -i xxd_data.bin > xxd_data.h`) to obtain the generated file (`xxd_data.h`) and add a null terminator if necessary:

```
unsigned char xxd_data_bin[] = {
    0x48, 0x65, 0x6c, 0x6c, 0x6f, 0x2c, 0x20, 0x57, 0x6f, 0x72, 0x6c, 0x64,
    0x0a, 0x00
};
unsigned int xxd_data_bin_len = 13;
```

2. Compile `main.c`:

```
#include <stdlib.h>
#include <stdio.h>

// prefix as const,
// even if it generates some warnings in g++/clang++
const
#include "xxd_data.h"

#define SIZE_OF_ARRAY (arr) (sizeof(arr) / sizeof(*arr))

int main() {
    const char* data = reinterpret_cast<const char*>(xxd_data_bin);
    puts(data); // Hello, World!
    return 0;
}
```

Others still use python or other small scripting languages as part of their build process, outputting data in the exact C++ format that they require.

There are problems with the `xxd -i` or similar tool-based approach. Tokenization and Parsing data-as-source-code adds an enormous overhead to actually reading and making that data available.

Binary data as C(++) arrays provide the overhead of having to comma-delimit every single byte present, it also requires that the compiler verify every entry in that array is a valid literal or entry according to the C++ language.

This scales poorly with larger files, and build times suffer for any non-trivial binary file, especially when it scales into Megabytes in size (e.g., firmware and similar).

8.1.2 python

Other companies are forced to create their own ad-hoc tools to embed data and files into their C++ code. MongoDB uses a [custom python script](#), just to format their data for compiler consumption:

```
import os
import sys

def jsToHeader(target, source):
    outFile = target
    h = [
        '#include "mongo/base/string_data.h"',
        '#include "mongo/scripting/engine.h"',
        'namespace mongo {',
        'namespace JSFiles{',
    ]
    def lineToChars(s):
        return ','.join(str(ord(c)) for c in (s.rstrip() + '\n')) + ','
    for s in source:
        filename = str(s)
        objname = os.path.split(filename)[1].split('.')[0]
        stringname = '__jscode_raw_' + objname

        h.append('constexpr char ' + stringname + "[] = {")

        with open(filename, 'r') as f:
            for line in f:
                h.append(lineToChars(line))

        h.append("};")
        # symbols aren't exported w/o this
        h.append('extern const JSFile %s;' % objname)
        h.append('const JSFile %s = { "%s", StringData(%s, sizeof(%s) - 1) };' %
            (objname, filename.replace('\\', '/'), stringname, stringname))

    h.append("} // namespace JSFiles")
    h.append("} // namespace mongo")
    h.append("")

    text = '\n'.join(h)

    with open(outFile, 'wb') as out:
        try:
            out.write(text)
        finally:
            out.close()

if __name__ == "__main__":
    if len(sys.argv) < 3:
        print "Must specify [target] [source] "
        sys.exit(1)
    jsToHeader(sys.argv[1], sys.argv[2:])
```

MongoDB were brave enough to share their code with me and make public the things they have to do: other companies have shared many similar concerns, but do not have the same bravery. We thank MongoDB for sharing.

8.1.3 1d

A complete example (does not compile on Visual C++):

1. Have a file `ld_data.bin` with the contents `Hello, World!`.
2. Run `ld -r binary -o ld_data.o ld_data.bin`.
3. Compile the following `main.cpp` with `c++ -std=c++17 ld_data.o main.cpp`:

```
#include <stdlib.h>
#include <stdio.h>

#define STRINGIZE_(x) #x
#define STRINGIZE(x) STRINGIZE_(x)

#ifdef __APPLE__
#include <mach-o/getsect.h>

#define DECLARE_LD_(LNAME) extern const unsigned char _section$__DATA_##LNAME[];
#define LD_NAME_(LNAME) _section$__DATA_##LNAME
#define LD_SIZE_(LNAME) (getsectbyLNAME("__DATA", "__" STRINGIZE(LNAME))->size)
#define DECLARE_LD(LNAME) DECLARE_LD_(LNAME)
#define LD_NAME(LNAME) LD_NAME_(LNAME)
#define LD_SIZE(LNAME) LD_SIZE_(LNAME)

#elif (defined __MINGW32__) /* mingw */

#define DECLARE_LD(LNAME) \
    extern const unsigned char binary_##LNAME##_start[]; \
    extern const unsigned char binary_##LNAME##_end[];
#define LD_NAME(LNAME) binary_##LNAME##_start
#define LD_SIZE(LNAME) ((binary_##LNAME##_end) - (binary_##LNAME##_start))
#define DECLARE_LD(LNAME) DECLARE_LD_(LNAME)
#define LD_NAME(LNAME) LD_NAME_(LNAME)
#define LD_SIZE(LNAME) LD_SIZE_(LNAME)

#else /* gnu/linux ld */

#define DECLARE_LD_(LNAME) \
    extern const unsigned char _binary_##LNAME##_start[]; \
    extern const unsigned char _binary_##LNAME##_end[];
#define LD_NAME_(LNAME) _binary_##LNAME##_start
#define LD_SIZE_(LNAME) ((_binary_##LNAME##_end) - (_binary_##LNAME##_start))
#define DECLARE_LD(LNAME) DECLARE_LD_(LNAME)
#define LD_NAME(LNAME) LD_NAME_(LNAME)
#define LD_SIZE(LNAME) LD_SIZE_(LNAME)
#endif

DECLARE_LD(ld_data_bin);

int main() {
    const char* p_data = reinterpret_cast<const char*>(LD_NAME(ld_data_bin));
    // impossible, not null-terminated
    //puts(p_data);
    // must copy instead
    return 0;
}
```

This scales a little bit better in terms of raw compilation time but is shockingly OS, vendor and platform

specific in ways that novice developers would not be able to handle fully. The macros are required to erase differences, lest subtle differences in name will destroy one's ability to use these macros effectively. We omitted the code for handling VC++ resource files because it is excessively verbose than what is present here.

N.B.: Because these declarations are `extern`, the values in the array cannot be accessed at compilation/translation-time.

8.1.4 `incbin`

There is a tool called [`incbin`](#) which is a 3rd party attempt at pulling files in at “assembly time”. Its approach is incredibly similar to `ld`, with the caveat that files must be shipped with their binary. It unfortunately falls prey to the same problems of cross-platform woes when dealing with Visual C, requiring additional pre-processing to work out in full.