补充与总结

Supplementary and Summary

现代C++基础
Modern C++ Basics

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- **File system**
- **Time utilities (Chrono)**
- **Math utilities**
- **Summary and future prospect**

Supplementary and Summary

File system

Overview

- Files represent organized data in non-volatile storage to let programs share data across different runs.
  - Files are named collection of data.
- Directories are used to construct file hierarchy.
  - Directories are named collection of files and directories.

- File system is an abstraction layer provided by OS to enable users to use *path* to access files and directories.
  - It records metadata of files and directories (size, modification time, owner, etc.) to make them organized and hierarchical.
- C++17 includes related utilities in `<filesystem>`.

Supplementary

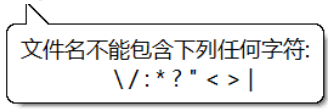
- File system
  - Path operations
    - Overview
    - std::filesystem::path
  - File system operations

Path Overview

- Essentially, path is a string that represents location of a file.
- There are two different kinds of paths:
  1. Absolute path: always refer to the same location.
  2. Relative path: the location relative to *current working directory* (CWD) for the current process.
     - By changing CWD, the process can get different locations.
- A path consists of these components:
  1. Root name (optional): like drive name in Windows (C:, D:); or UNC (`//machine`), etc.
  2. Root directory (optional): a directory separator (`\` on Windows, `/` on Linux, `:` on classic MacOS).
  3. Relative path: a sequence of filenames separated by directory separator.

Path Overview

- Besides no separators, filenames have many other platform-dependent characteristics or restrictions.

(1.1) — The permitted characters. e.g. on Windows: 

[*Example 1*: Some operating systems prohibit the ASCII control characters (0x00 – 0x1F) in filenames. — *end example*]

[*Note 1*: Wider portability can be achieved by limiting *filename* characters to the POSIX Portable Filename Character Set:
`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`
`0 1 2 3 4 5 6 7 8 9 . _ -` — *end note*]

(1.2) — The maximum permitted length. e.g. well-known 260 in some Windows functions.

(1.3) — Filenames that are not permitted.

(1.4) — Filenames that have special meaning. e.g. CON on Windows.

(1.5) — Case awareness and sensitivity during path resolution. e.g. Linux is case-sensitive while Windows not.

(1.6) — Special rules that may apply to file types other than regular files, such as directories.

Particularly, `.` and `..` means current directory and parent directory respectively.

Path Overview

- To make program cross-platform, C++ regulates a “generic format” that uses POSIX convention.
  - That is, these three components are just concatenated to form a path.
    - And / is considered as universal separator.
- Besides, C++ allows “native format” that depends on file system.
  - E.g. OpenVMS, a legacy system previously used in bank (well, if it really supports C++17 utilities).

What Is a Fully Qualified Name?

A *fully qualified name* indicates how a file fits into a structure (a system of directories and subdirectories) that contains all the files stored under the OpenVMS system. The following type of file specification is a fully qualified name:

node::*device*:[*directory*]*filename*.*file-type*;*version* e.g. DKA0:[JDOE.DATA]test.txt

Path Overview

- Note 1: “generic” only means it’s a valid format in all systems; but its location is not always the same.
  - What is `D:\sub\path`?
    - Windows: an absolute path at D drive, with two components `sub` and `path`.
    - Linux: a relative path with name “`D:\sub\path`”, i.e. the whole string is a single component.
  - What is `/home/user`?
    - Linux: an absolute path with two components `home` and `user`.
    - Windows: a relative path at drive of CWD, with two components `home` and `user`.
- Note 2: it’s not very safe to rely on relative path since it’s just like a global variable, which can be changed by other threads and external library.
  - i.e. the location of a relative path can be modified arbitrarily.

Path Overview

- Note 3: “relative” or “absolute” only means whether it’s interfered by CWD; there can be many paths that refer to the same location.
  - E.g. `/home/user`, `/home/user/.`, `/home/user/dir/..`, ….
  - To unify all representations, we can do *path normalization*.
  - There are two kinds of normalization:
    - Lexical: a string-level substitution, which doesn’t change whether the path is relative or absolute.
      - So `/home/user`, `/home/user/.`, `/home/user/dir/..` are all normalized to `/home/user`, and paths `./user`, `./user/.`, `./user/dir/..` are all normalized to `user`.
    - Filesystem-dependent: paths are normalized to a unique absolute path.
      - Assuming CWD is `/home`, `./user`, `./user/.`, `./user/dir/..` are all normalized to `/home/user`.
      - C++ call such normalization as “canonical”.

Path Overview

- Specifically, a normalized path requires:

A path might be or can become normalized. In a normalized path:

- File names are separated only by a single preferred directory separator.
- The file name " . " is not used unless the whole path is nothing but " . " (representing the current directory).
- The file name does not contain " . . " file names (we do not go down and then up again) unless they are at the beginning of a relative path.
- The path only ends with a directory separator if the trailing file name is a directory with a name other than " . " or " . . ".

Path	POSIX normalized	Windows normalized
`foo/.///bar/../`	`foo/`	`foo\`
`//host/../foo.txt`	`//host/foo.txt`	`\\host\foo.txt`
`./f/../.f/`	`.f/`	`.f\`
`C:bar/../`	`.`	`C:`
`C:/bar/..`	`C:/`	`C:\`
`C:\bar\..`	`C:\bar\..`	`C:\`
`/./../data.txt`	`/data.txt`	`\data.txt`
`././`	`.`	`.`

POSIX may or may not respect //.

(Due to UNC path)

Credit: C++17 the Complete Guide, *Nicolai M. Josuttis*.

Supplementary

- File system
  - Path operations
    - Overview
    - std::filesystem::path
  - File system operations

For brevity, we use `namespace stdfs = std::filesystem`.

Path

- C++ uses `stdfs::path` to represent a path.
  - It is essentially a string of some *native encoding*, e.g. UTF-8 on Linux, UTF-16 on Windows*.
    - The underlying character can be checked by `stdfs::path::value_type`, normally `char` on Linux and `wchar_t` on Windows.
    - And `stdfs::path::string_type = std::basic_string<value_type>`.
  - And the string stores path in *native format*.
  - You can just access the underlying string in `const` way:

Accesses the native path name as a character string.

```
const value_type* c_str() const noexcept;          (1)
const string_type& native() const noexcept;        (2)
operator string_type() const;                      (3)
```

1) Equivalent to `native().c_str()`.
2) Returns the native-format representation of the pathname by reference.
3) Returns the native-format representation of the pathname by value.

*: Strictly speaking, usually a filesystem doesn't really respect encoding; it just treats the path as some byte sequence (even if it's not a valid UTF-8 / 16). So "native encoding" essentially means "a string that you can pass into filesystem syscall directly", e.g. 2-byte-per-unit sequence on Windows.

Path

Exceptions

2,4-8) May throw implementation-defined exceptions.

- However, you can construct the path by any encoding and format.

```
template< class Source >
path( const Source& source, format fmt = auto_format );

template< class InputIt >
path( InputIt first, InputIt last, format fmt = auto_format );
```

  - For `format`, it's essentially a scoped enumeration in `stdfs::path` with three enumerators:

Name	Explanation
`native_format`	native pathname format
`generic_format`	generic pathname format
`auto_format`	implementation-defined format, auto-detected where possible

  - By default it uses `auto_format`, i.e. determine if the input format is native or generic automatically and convert if necessary.

Path

```
template< class Source >
path( const Source& source, format fmt = auto_format );

template< class InputIt >
path( InputIt first, InputIt last, format fmt = auto_format );
```

- The template allows you to use any character type, and ctor will convert to its native encoding.

(2.1) — `char`: The encoding is the native ordinary encoding. The method of conversion, if any, is operating system dependent.

(2.2) — `wchar_t`: The encoding is the native wide encoding. The method of conversion is unspecified.

(2.3) — `char8_t`: The encoding is UTF-8. The method of conversion is unspecified.

(2.4) — `char16_t`: The encoding is UTF-16. The method of conversion is unspecified.

(2.5) — `char32_t`: The encoding is UTF-32. The method of conversion is unspecified.

  - For `wchar_t`, Windows won't do any conversion but Linux needs to do so;
  - For `char`, Linux won't do any conversion but Windows needs to do so.
- Actually, Windows recognizes `char` for file API in ANSI (or Active) Code Page (ACP).
  - This will lead to complex behavior when interacting with compiler option…

Windows ACP

- Assuming that we have a file path “D:\试验.txt” on Windows.
  - And we use a default Chinese PC, i.e. ACP is GBK (id: 936).
- Given `main.cpp` as:

```cpp
std::filesystem::path p{ R"(D:\试验.txt)" };
std::cout << std::filesystem::exists(p) << "\n";
```

Check whether some path exists, equiv. to `std::ifstream{p}.is_open()` if `p` is a file instead of directory.

- Case 1: msvc doesn’t add any option, and encoding of `main.cpp` is GBK.
  1. `D:\试验.txt` is in GBK, and msvc reads it as GBK correctly.
  2. The execution charset is GBK, so `D:\试验.txt` is still GBK in binary exe.
  3. Current ACP is GBK, so `stdfs::path` converts it from GBK to native encoding (UTF-16) and stores it;
  4. The path is correct so file system says it exists.

Windows ACP

```
std::filesystem::path p{ R"(D:\试验.txt)" };
std::cout << std::filesystem::exists(p) << "\n";
```

- Case 2: msvc adds `/utf-8`, and encoding of `main.cpp` is UTF-8.
  1. `D:\试验.txt` is in UTF-8, and msvc reads it as UTF-8 correctly.
  2. The execution charset is UTF-8, so `D:\试验.txt` **is UTF-8** in binary exe.
  3. Current ACP is GBK, so `stdfs::path` converts it **from GBK** to native encoding (UTF-16) and stores it;
     - However, UTF-8 string is not really a GBK string, and the corresponding binary leads to GBK as "`D:\璇曢獙.txt`".
  4. The path is not correct and file system says it doesn't exist.
- Case 3: msvc adds `/source-charset:utf-8`, and encoding of `main.cpp` is UTF-8.
  1. `D:\试验.txt` is in UTF-8, and msvc reads it as UTF-8 correctly.
  2. As default execution charset is ACP, `D:\试验.txt` **is GBK** in binary exe.
  3. So the path is still correct and file system says it exists.

Windows ACP

```
std::filesystem::path p{ R"(D:\试验.txt)" };
std::cout << std::filesystem::exists(p) << "\n";
```

- Case 4: msvc adds `/utf-8`, and encoding of `main.cpp` is GBK.
  1. `D:\试验.txt` in GBK is not valid UTF-8, so msvc warns C4828 (illegal character in UTF-8) and silently passes the original bytes as is.
     - So **accidentally**, it's still GBK in binary exe.
  2. Thus accidentally, the path is correct and file system says it exists.
- Case 5: assuming ACP is UTF-8 (65001), msvc doesn't add any option (equiv. to add `/utf-8`), and encoding of `main.cpp` is GBK.
  1. Same as case 4, i.e. the string is of GBK in binary exe.
  2. However, GBK is not valid UTF-8, so ctor of path throws an exception (`std::system_error` in MS-STL).

Path construction

- So to make a valid path, we need first:
  - Make sure the compiler knows how to read the file (string literals), i.e. the file encoding should be correctly specified in source charset.
- And then two ways:
  1. Make execution charset (for string literals) and string encoding (for other strings stored in e.g. `std::string`) same as ACP.
  2. Use `char8_t[] / char16_t[] / char32_t[]` instead.
     A. Any ACP is OK, since `char8_t` as a unique type will always be decoded as UTF-8 in ctor.
     B. Any execution charset is OK, since `char8_t` is always UTF-8 in binary exe.

```
std::filesystem::path p{ u8R"(D:\试验.txt)" };
```

- And if you know your `std::string / …` is essentially UTF-8 while ACP is not, you can `reinterpret_cast` it to avoid conversion.

```
// Assuming we use UTF-8 as execution charset.
std::string s{ R"(D:\试验.txt)" };
auto ptr = reinterpret_cast<const char8_t *>(s.c_str());
std::u8string_view view{ ptr, ptr + s.size() / sizeof(char8_t) };
std::filesystem::path p{ view };
```

Path construction

- On the other hand, on Linux + gcc, no matter what execution charset you use, `char[]` won't do any conversion.
  - As `char` is its native encoding, so libstdc++ assumes correct bytes.
  - Instead, `-fwide-exec-charset` will specify encoding of `wchar_t` and be converted to UTF-8 automatically.
- To specify encoding and conversion explicitly, you can use locale:

```
template< class Source >
path( const Source& source, const std::locale& loc, format fmt = auto_format );
```

```
template< class InputIt >
path( InputIt first, InputIt last, const std::locale& loc, format fmt = auto_format );
```

  - As the conversion is explicitly specified in locale, the template only accepts a char sequence.

Path const

```
path& operator=( const path& p );
path& operator=( path&& p ) noexcept;
path& operator=( string_type&& source );
template< class Source >
path& operator=( const Source& source );
```

```
path& assign( string_type&& source );
template< class Source >
path& assign( const Source& source );
template< class InputIt >
path& assign( InputIt first, InputIt last );
```

- When native encoding is `wchar_t`:
  - Just use `codecvt<wchar_t, char, std::mbstate_t>` in locale to convert `char[]` to native encoding `wchar_t[]`.
    - E.g. For windows, GBK -> UTF-16.
- When native encoding is `char`:
  - First use `codecvt<wchar_t, char, std::mbstate_t>` in locale to convert `char[]` to `wchar_t[]`;
    - E.g. For Linux, GBK -> UTF-32
  - Then convert `wchar_t` back to native encoding `char` (e.g. UTF-8).
    - E.g. UTF-32 -> UTF-8, which is equiv. to construct from `wchar_t[]` directly.

- And finally some omitted overloads & `operator=`, just list here.

```
path() noexcept;
```
Default is just an empty string.

```
path( const path& p );
path( path&& p ) noexcept;
path( string_type&& source, format fmt = auto_format );
```

Path

- Besides construction, you can also get string of different formats and encodings.
  - Native format + Native encoding: just `.native()`, as we mentioned.
  - Native format + Converted encoding:

```
std::string string() const;
std::wstring wstring() const;
std::u16string u16string() const;
std::u32string u32string() const;

std::u8string u8string() const;
```

  - Generic format + Converted encoding:

```
std::string generic_string() const;
std::wstring generic_wstring() const;
std::u16string generic_u16string() const;
std::u32string generic_u32string() const;
```
(2) (since C++17)

```
std::u8string generic_u8string() const;
```
(3) (since C++20)

    - Particularly, these functions are required to use `/` as directory separator.

Path

- And there are also template versions, together will allocator:

```
template< class CharT, class Traits = std::char_traits<CharT>,
          class Alloc = std::allocator<CharT> >
std::basic_string<CharT,Traits,Alloc>
    string( const Alloc& a = Alloc() ) const;                    (1)
```

```
template< class CharT, class Traits = std::char_traits<CharT>,
          class Alloc = std::allocator<CharT> >
std::basic_string<CharT,Traits,Alloc>
    generic_string( const Alloc& a = Alloc() ) const;            (1)
```

  - So to get Generic format + Native encoding, just use `.generic_string<stdfs::path::value_type>()`.
- Finally, you can also check the preferred separator by `static constexpr stdfs::path::preferred_separator`.
  - `\` on Windows, `/` on Linux.

Path decomposition

Note: filename with pure extension (e.g. `"D:\\.gitignore"`) is not considered as extension (i.e. stem = filename = `".gitignore"`, extension = `""`)

- There are also some observer functions to query path components:
  - which just return new `stdfs::path`.

`root_name`

`root_directory`

`root_path`

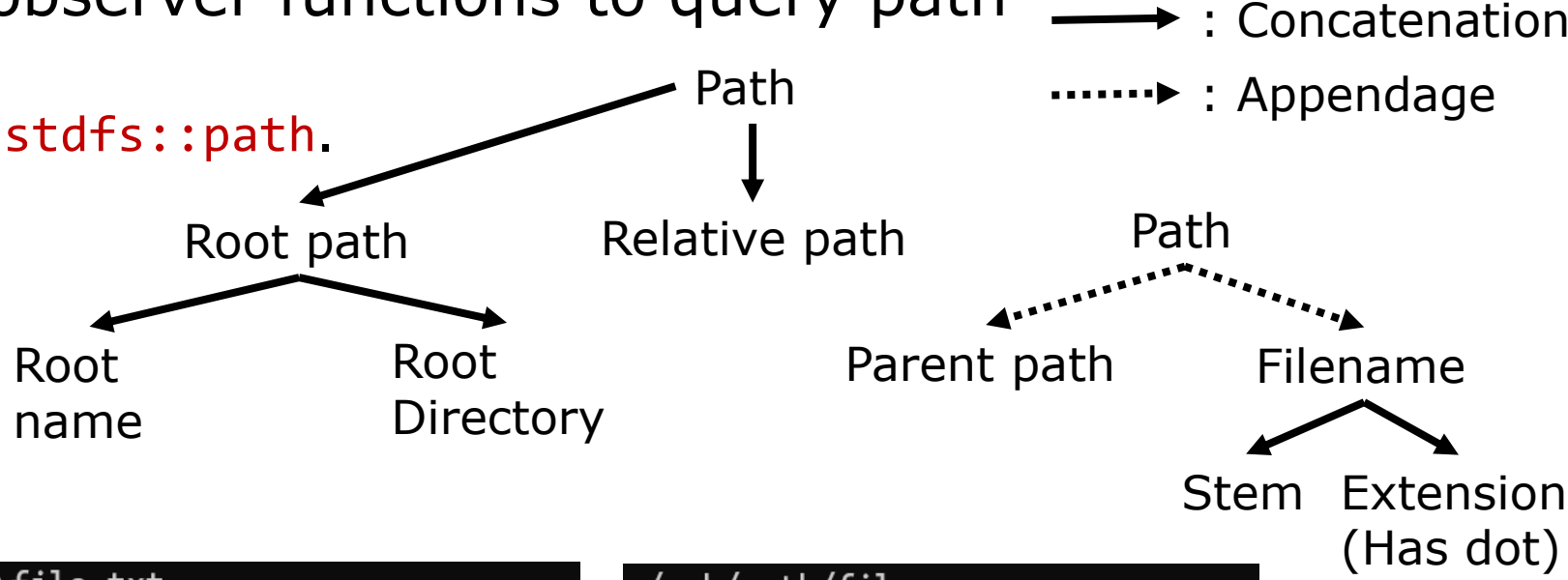
`relative_path`

`parent_path`

`filename`

`stem`

`extension`




```
D:\sub\path\file.txt
Original path = "D:\\sub\\path\\file.txt"
Root name = "D:"
Root directory = "\\"
Root path = "D:\\"
Relative path = "sub\\path\\file.txt"
Parent path = "D:\\sub\\path"
Filename = "file.txt"
Stem = "file"
Extension = ".txt"
```

```
./sub/path/file
Original path = "./sub/path/file"
Root name = ""
Root directory = ""
Root path = ""
Relative path = "./sub/path/file"
Parent path = "./sub/path"
Filename = "file"
Stem = "file"
Extension = ""
```

Path decomposition

- Particularly, such decomposition is **lexical**, which doesn't even really interact with file system.
  - So "parent path" doesn't really return path of parent directory, but just remove the last component.
    - And when a path ends with directory separator, the last component is just empty, so parent just removes the separator.

- For example:

```
D:\sub\path\file\
Original path = "D:\\sub\\path\\file\\"
Root name = "D:"
Root directory = "\\"
Root path = "D:\\"
Relative path = "sub\\path\\file\\"
Parent path = "D:\\sub\\path\\file"
Filename = ""
Stem = ""
Extension = ""
```

```
./sub/path/..
Original path = "./sub/path/.."
Root name = ""
Root directory = ""
Root path = ""
Relative path = "./sub/path/.."
Parent path = "./sub/path"
Filename = ".."
Stem = ".."
Extension = ""
```

Note: parent of root directory is still root directory (i.e. `"/" -> "/"`);
but parent of file name is empty (i.e. `"data.txt" -> ""`).

Path normalization

- To find real parent, you need to do path normalization first.
  - And we say that there are two ways:
  - Lexical: by `.lexically_normal()`; the normalization process is:

Normalization of a generic format pathname means:

Assuming we have a path as "D:/..\sub\.\/path\..\file.txt".

1. If the path is empty, stop.

D:/..\sub\.\/path\..\file.txt

2. Replace each slash character in the *root-name* with a *preferred-separator*.

D:\..\sub\.\/path\..\file.txt

3. Replace each *directory-separator* with a *preferred-separator*.

   [*Note 4*: The generic pathname grammar defines *directory-separator* as one or more slashes and *preferred-separators*. — *end note*]

D:\..\sub\.\path\..\file.txt

4. Remove each dot filename and any immediately following *directory-separator*.

D:\..\sub\path\..\file.txt

5. As long as any appear, remove a non-dot-dot filename immediately followed by a *directory-separator* and a dot-dot filename, along with any immediately following *directory-separator*.

D:\..\sub\file.txt

6. If there is a *root-directory*, remove all dot-dot filenames and any *directory-separators* immediately following them.

D:\sub\file.txt

   [*Note 5*: These dot-dot filenames attempt to refer to nonexistent parent directories. — *end note*]

7. If the last filename is dot-dot, remove any trailing *directory-separator*.

7. is applied to e.g. ..\..\.

8. If the path is empty, add a dot.

1. & 8. An empty path is still empty after normalization, but a non-empty but essentially empty is normalized to ..

Path normalization

- Filesystem-dependent: `stdfs::canonical / weakly_canonical`; paths are normalized to a unique absolute path.
  - Path is first converted to an absolute path by `stdfs::absolute(p)`;
  - Then perform lexical normalization.

  - `canonical` will check whether the path really exists, while `weakly_canonical` just normalizes it.
  - We'll go into details about two forms of global APIs in `stdfs` later.

```
path canonical( const std::filesystem::path& p );                    (1)
path canonical( const std::filesystem::path& p,
                std::error_code& ec );                               (2)
path weakly_canonical( const std::filesystem::path& p );             (3)
path weakly_canonical( const std::filesystem::path& p,
                       std::error_code& ec );                        (4)
```

Example

```cpp
std::filesystem::path p{ s };
std::cout << "Original path = " << p << "\n";
std::cout << "-------------- Lexical normal --------------\n";
OutputProperties(p.lexically_normal());
std::cout << "-------------- Weakly canonical --------------\n";
OutputProperties(std::filesystem::weakly_canonical(p));
```

```
Original path = "./sub/path/.."
-------------- Lexical normal --------------
Path = "sub/"
Root name = ""
Root directory = ""
Root path = ""
Relative path = "sub/"
Parent path = "sub"
Filename = ""
Stem = ""
Extension = ""
-------------- Weakly canonical --------------
Path = "/app/sub/"
Root name = ""
Root directory = "/"
Root path = "/"
Relative path = "app/sub/"
Parent path = "/app/sub"
Filename = ""
Stem = ""
Extension = ""
```

The last `/` is not stripped, even after normalization. `..` only removes **trailing** `/`.

```
Original path = "./sub/path/"
-------------- Lexical normal --------------
Path = "sub/path/"
Root name = ""
Root directory = ""
Root path = ""
Relative path = "sub/path/"
Parent path = "sub/path"
Filename = ""
Stem = ""
Extension = ""
-------------- Weakly canonical --------------
Path = "/app/sub/path/"
Root name = ""
Root directory = "/"
Root path = "/"
Relative path = "app/sub/path/"
Parent path = "/app/sub/path"
Filename = ""
Stem = ""
Extension = ""
```

Path normalization

- Notice that “physical” parent of lexical normalization may still be wrong when normalized result still contains `..`.
  - Only `(weakly_)canonical` ensures a correct physical parent.

```
Original path = "../.."
-------------- Lexical normal --------------
Path = "../.."
Root name = ""
Root directory = ""
Root path = ""
Relative path = "../.."
Parent path = ".."
Filename = ".."
Stem = ".."
Extension = ""
```

- Finally, you can get or set CWD by `current_path()`:

```
std::cout << std::filesystem::current_path() << "\n";
std::filesystem::current_path("C:\\Temp");
std::cout << std::filesystem::current_path() << "\n";
```

```
"D:\\Work\\C++\\Tests\\Project1"
"C:\\Temp"
```

  - So `absolute()` is essentially `current_path() / path` when `path` is relative.

DOS directory

```
C:\Users\Public>cd D:\Work

C:\Users\Public>D:

D:\Work>C:

C:\Users\Public>
```

cd: change current directory

"D:" : switch to current directory of Drive D.

"C:" : switch to current directory of Drive C.

- It's also worth nothing that DOS maintains separate "current directory" for every drive.
  - So `C:` and `D:` are actually relative paths, while `C:\` and `D:\` are absolute paths.
- In Windows, current directory is unified as a single path, as known by CWD.
  - However, CMD pretends they are still there by storing them with "strange environment variables".
  - And Windows inherits the DOS behavior, regarding `C:` and `D:` as relative paths. But there exists only a single real CWD.

```
std::cout << std::filesystem::current_path() << "\n";
std::cout << std::filesystem::absolute("C:") << "\n";
std::cout << std::filesystem::absolute("D:") << "\n";
std::filesystem::current_path("C:\\Temp");
std::cout << std::filesystem::absolute("C:") << "\n";
std::cout << std::filesystem::absolute("D:") << "\n";
```

```
"D:\\Work\\C++\\Tests\\Project1"
"C:\\"
"D:\\Work\\C++\\Tests\\Project1"
"C:\\Temp"
"D:\\"
```

Other non-CWD drive will return root.

1: term “relativization” is from Java.nio.

Path relativization[1]

- In contrast to normalization, path can also be “denormalized” by converting an absolute path to relative path.
  - More generally, given a path `b`, how can it be transformed to path `a` with shortest components.
  - For example, `path{ "/a/d" }.relative("/a/b/c")` would be `"../../d"`.
- Similarly, you can use two ways:
  - Lexical: by `a.lexically_relative(b)`; the process is:
    ① Check whether it’s possible to transform `b` to `a`.
      - If it’s impossible (i.e. conditions below), return empty path directly.

— `root_name() != base.root_name()` is `true`, or — E.g. two paths in different drives in Windows.

— `is_absolute() != base.is_absolute()` is `true`, or — Absolute path + relative path, not lexically transformable.

— `!has_root_directory() && base.has_root_directory()` is `true`, or — E.g. `bar` and `/foo` on Windows, i.e. you cannot cd from `/foo` to `bar` without CWD.

— any *filename* in `relative_path()` or `base.relative_path()` can be interpreted as a *root-name*,

E.g. for UNC path on Windows, e.g. `\\.\C:\Test` uses `C:\Test` as relative path.
That is, UNC doesn’t participate in lexical relative process.

Path relativization

```
a = D:\test\test.txt
b = D:\test\test2\test.txt\..
```

② Determine the first mismatched component of two paths (just like `std::mismatch`).

- Let remaining mismatched components of `a` be $[a_1, a_2)$ and `b` be $[b_1, b_2)$;
  - Example above is $[a_1, a_2) = [test.txt], [b_1, b_2) = [test2, test.txt, ..]$.
- If no mismatched component (i.e. $a_1 = a_2, b_1 = b_2$), return `path{ “.” }`;
- Otherwise, assuming that in $[b_1, b_2)$, n components are `..` and m components are not `..`, `.` and empty.
  - Example above is $n = 1, m = 2$.
  - If $n > m$ (that is, the lexically normalized form contains only `..`), then return empty path.
  - If $n = m$ (that is, the lexically normalized form is `.`), then:
    - If $a_1 = a_2$, return `path{ “.” }`;
    - Otherwise, return $[a_1, a_2)$.
  - If $n < m$, then return a path with 1. `".."` repeated for $m - n$ times; 2. $[a_1, a_2)$.

```
result = ..\test.txt
```

Path relativization

- Actually, this algorithm may falsely report empty path even when such transformation should be possible.
  - For example:

```
fs::path p{ "a/b"};
std::cout << p.lexically_relative("a/b/..") << "\n";
```

$n = 1, m = 0$

```
Program returned: 0
    ""
```

    - Though theoretically it can be “..”.
  - If you want an always-correct lexical transformation, you need to do lexical normalization first.

[*Note 3*: If normalization ([fs.path.generic]) is needed to ensure consistent matching of elements, apply `lexically_normal()` to `*this`, `base`, or both. — *end note*]

- The second way is filesystem-dependent `stdfs::relative(a, b)`, which will always ensure correct relative path in the file system.
  - It’s same as `lexically_relative` two `weakly_canonical` paths.

Path proximation

- Finally there also exists proximation, which means “relativization if possible, otherwise return original path”.
  - Effectively:

```
path lexically_proximate(const path& b)
{
    if (auto rel = a.lexically_relative(b); !rel.empty())
        return rel;
    return *this;
}
```

  - And `stdfs::proximate(a, b)` is also same as `lexically_proximate` two `weakly_canonical` paths.
  - BTW, when `b` is not provided in `relative` and `proximate`, `current_directory` will be used.

```
friend path operator/( const path& lhs, const path& rhs );
```

```
path& operator/=( const path& p );

template< class Source >
path& operator/=( const Source& source );

template< class Source >
path& append( const Source& source );

template< class InputIt >
path& append( InputIt first, InputIt last );
```

Path composition

- For a given path `./sub/path/file.txt`, it's essentially a combination of hierarchical components.
- C++ provides two utilities to combine components.
  1. Append: combine two components with a directory separator, if needed.
     - For example: (on Linux)

```
std::filesystem::path p = "/home";
//  p == /home/tux/.fonts
std::cout << p / "tux" / ".fonts" << '\n';
```

```
std::filesystem::path p = "/home";
//  p == /home/tux/.fonts
std::cout << p / "tux/" / ".fonts" << '\n';
```

     - However, there exist lots of corner cases…

     ① Subpath is absolute path: C++ chooses to overwrite (replace) LHS.
       - For example:

```
// On Windows,
path("foo") / "C:/bar";  // the result is "C:/bar" (replaces)
```

       - But this can be astonishing:

```
std::filesystem::path p = "/home";
//  p == /.fonts
std::cout << p / "tux" / "/.fonts" << '\n';
```

       Reason: "/.fonts" is absolute path.

Path composition

- DOS-like behavior on Windows also causes surprising result even when subpath is relative.
  - ② No separator is inserted for a single drive; it's still a relative path.

```
std::cout << fs::path{ "C:" } / "Users" / "Admin" << '\n';
std::cout << fs::path{ "C:\\" } / "Users" / "Admin" << '\n';
```

```
"C:Users\\Admin"
"C:\\Users\\Admin"
```

  - ③ Appending a relative path that has different drive will replace the whole path;

```
path("foo") / "C:/bar";  // the result is "C:/bar" (replaces)
path("foo") / "C:";      // the result is "C:"     (replaces)
```

  - ④ Appending a relative path that has same drive will append as if LHS is CWD.

```
std::cout << fs::path{ "C:\\foo" } / "C:bar" << "\n";
std::cout << fs::path{ "C:foo" } / "C:bar" << "\n";
```

```
"C:\\foo\\bar"
"C:foo\\bar"
```

  - ⑤ Appending a relative path that has root directory but no drive, to another path with drive will reserve LHS drive.

```
std::cout << fs::path{ "C:\\bar" } / "\\foo" << "\n";
std::cout << fs::path{ "C:bar" } / "\\foo" << "\n";
```

```
"C:\\foo"
"C:\\foo"
```

Path composition

```
template< class Source >
path& concat( const Source& source );                    (7)

template< class InputIt >
path& concat( InputIt first, InputIt last );             (8)
```

2. Concatenate: combine two components as if concatenating underlying strings directly; no additional separator is introduced.

```
path& operator+=( const path& p );                       (1)

path& operator+=( const string_type& str );
path& operator+=( std::basic_string_view<value_type> str );   (2)

path& operator+=( const value_type* ptr );               (3)

path& operator+=( value_type x );                        (4)

template< class CharT >
path& operator+=( CharT x );                             (5)

template< class Source >
path& operator+=( const Source& source );                (6)
```

These overloads are designed to mimic overloads of `std::string::operator+=`.

- Strangely, there is no `operator+`; but normally this operation is used to concatenate with a string, so you can just `operator+` all strings first.
  - Or you have to use either `((stdfs::path{a} += b) += c)`… or `.native()` to use `operator+` of `std::basic_string`.

Path composition

- Note 1: Due to associativity, `p / "a" / "b"` is legal while `p /= "a" /= "b"` is illegal.
  - `p / "a" / "b"` ⇔ `((p / "a") / "b")`, while
  - `p /= "a" /= "b"` ⇔ `(p /= ("a" /= "b"))`.
    - And it's illegal for two string literals to `/=`.
  - You have to add a bunch of brackets; that's why we use `((stdfs::path{a} += b) += c)…`.
- Note 2: there also exist some boolean observers to check existence.
  - "empty" means the underlying string contains nothing.
  - And `has_xxx` means whether `xxx` is empty or not.

```
empty

has_root_path
has_root_name
has_root_directory
has_relative_path
has_parent_path
has_filename
has_stem
has_extension

is_absolute
is_relative
```

Path iteration

- As a combination of many different components, path can also be iterated (grouped by separator) in generic format.
- It provides `.begin()` and `.end()` that return a path const iterator.
  - It just iterates through root name, root directory and filenames.
  - For example:

```cpp
#include <filesystem>
#include <iostream>
namespace fs = std::filesystem;

int main()
{
    const fs::path p =
#   ifdef _WIN32
        "C:\\users\\abcdef\\AppData\\Local\\Temp\\";
#   else
        "/home/user/.config/Cppcheck/Cppcheck-GUI.conf";
#   endif
    std::cout << "Examining the path " << p << " through iterators gives\n";
    for (auto it = p.begin(); it != p.end(); ++it)
        std::cout << *it << " | ";
    std::cout << '\n';
}
```

```
--- Windows ---
Examining the path "C:\users\abcdef\AppData\Local\Temp\" through iterators gives
"C:" | "/" | "users" | "abcdef" | "AppData" | "Local" | "Temp" | "" |

--- UNIX ---
Examining the path "/home/user/.config/Cppcheck/Cppcheck-GUI.conf" through iterators gives
"/" | "home" | "user" | ".config" | "Cppcheck" | "Cppcheck-GUI.conf" |
```

Deferenced result (i.e. `iterator::value_type`) is another `path`.

Path iteration

- Though it seems to be bidirectional iterator, it's actually only regulated to be input iterator.
  - Reason: before C++20, forward iterator has such a regulation:

> If `i` and `j` are both dereferenceable, then `i == j` if and only if `*i` and `*j` are bound to the same object.

  - That is, every component should have a fixed source to make every iterator dereferenced to that source.
  - This requires `path` to store a container of components, making it expensive to construct any `path`…
    - And this is how libstdc++ implements it, making it bidirectional.
- However, path iterator is quite like a string `std::views::split` by separator!
  - Another way (as libc++ and MS-STL do) is to cache the range in the iterator, so only when iterator is used will parsing begins.

Issue 2674: Bidirectional iterator requirement on path::iterator is very expensive

Path iteration

- So instead, the standard regulates that:

> 2 A `path::iterator` is a constant iterator meeting all the requirements of a bidirectional iterator except that, for dereferenceable iterators `a` and `b` of type `path::iterator` with `a == b`, there is no requirement that `*a` and `*b` are bound to the same object. Its `value_type` is `path`.

  - which makes it only satisfies input iterator, and thus it's impossible to apply some functions in `<algorithm>`.
- BUT, such requirement is not part of `bidirectional_iterator` in C++20!
  - So theoretically it should be able to utilize constrained algorithms, i.e. `std::ranges::xxx`.
  - I'm currently planning to submit a DR or proposal to solve this problem (if you're a committee, feel free to contact me ☺).

Path modification

Modifiers

- clear
- make_preferred
- remove_filename
- replace_filename
- replace_extension
- swap

Return reference to *this.

- There also exist some simple non-const methods:
  1. .make_preferred(): for path whose native format is also generic format, convert current separators to preferred separators.
     - For example:

```
fs::path p{ "C:/Test\\Test2" };
std::cout << p << "\n" << p.make_preferred() << "\n";
```

```
"C:/Test\\Test2"
"C:\\Test\\Test2"
```

  2. .remove_filename(): Remove the last component (if it exists) so .has_filename() returns false.
     - So after removal, the path is either empty or ends with a separator.

```
std::cout << std::boolalpha
          << (p = "foo/bar").remove_filename()
          << (p = "foo/").remove_filename() <<
          << (p = "/foo").remove_filename() <<
          << (p = "/").remove_filename() << '\
          << (p = "").remove_filename() << '\t
```

```
"foo/"
"foo/"
"/"
"/"
""
```

“foo” will also be converted to “”.

Path modification

3. `.replace_filename(const path& rep)`: equivalent to 1. `this->remove_filename()`; 2. `(*this) /= rep`.
4. `.replace_extension(const path& rep = {})`: equivalent to code below:
   - For example:

Path:	Ext:	Result:
"/foo/bar.jpg"	".png"	"/foo/bar.png"
"/foo/bar.jpg"	"png"	"/foo/bar.png"
"/foo/bar.jpg"	"."	"/foo/bar."
"/foo/bar.jpg"	""	"/foo/bar"
"/foo/bar."	"png"	"/foo/bar.png"
"/foo/bar"	".png"	"/foo/bar.png"
"/foo/bar"	"png"	"/foo/bar.png"
"/foo/bar"	"."	"/foo/bar."
"/foo/bar"	""	"/foo/bar"
"/foo/."	".png"	"/foo/..png"
"/foo/."	"png"	"/foo/..png"
"/foo/."	"."	"/foo/.."
"/foo/."	""	"/foo/."
"/foo/"	".png"	"/foo/.png"
"/foo/"	"png"	"/foo/.png"

```
// Assume we have a function TryRemoveExtension,
// which will remove extension if it exists.
path& ReplaceExtension(const path& rep = {})
{
    TryRemoveExtension();
    if (rep.empty)
        return *this;
    // Add '.' if necessary
    if (rep.native()[0] != DOT)
        this->concat(DOT);
    return *this += rep;
}
```

Path

1) If `root_name().native().compare(p.root_name().native())` is nonzero, returns that value.

Otherwise, if `has_root_directory() != p.has_root_directory()`, returns a value less than zero if `has_root_directory()` is `false` and a value greater than zero otherwise.

Before element-wise comparison, it needs to judge these conditions first.

- And finally some simple utilities, just list here.
  - Comparable (by `<=>/==` or `.compare`); compare **components**. e.g. `"D:/Test" == "D://Test"`
  - Hashable (by `std::hash` or `friend hash_value`); hash components.
  - Input / Output by >> / <<;
    - For `i/ostream<CharT, Traits>`, equiv. to input / output the `.string<CharT, Traits>()` with `std::quoted` so space will not interrupt input.
    - Recap: `quoted` will escape the quote and the escape, so `\` is escaped to `\\`.
  - Formattable **since C++26**.

```
"C:\\foo\\bar"
"C:foo\\bar"
```

Format specification

The syntax of format specifications *path-format-spec* is:

fill-and-align(optional) *width*(optional) **?**(optional) **g**(optional)

fill-and-align and *width* have the same meaning as in standard format specification.

The **?** option is used to format the pathname as an escaped string.

The **g** option is used to specify that the pathname is in generic-format representation.

Path formatting

- Its regulation is slightly different from `.string()`.

std::formatter<std::filesystem::path>::format

```
template< class FormatContext >
auto format( const std::filesystem::path& p, FormatContext& ctx ) const
    -> FormatContext::iterator;
```

Let `s` be `p.generic_string<std::filesystem::path::value_type>()` if the **g** option is used, otherwise `p.native()`. Writes `s` into `ctx.out()` as specified by *path-format-spec*.

For character transcoding of the pathname:

- The pathname is transcoded from the native encoding for wide character strings to UTF-8 with maximal subparts of ill-formed subsequences substituted with U+FFFD REPLACEMENT CHARACTER if
  - `std::is_same_v<CharT, char>` is `true`,
  - `std::is_same_v<typename path::value_type, wchar_t>` is `true`, and
  - ordinary literal encoding is UTF-8.
- Otherwise, no transcoding is performed if `std::is_same_v<typename path::value_type, CharT>` is `true`.
- Otherwise, transcoding is implementation-defined.

Returns an iterator past the end of the output range.

i.e. encoding of char string literal, as specified in compiler execution charset option.

i.e. explicitly regulate that in UTF-8 execution charset on Windows, illegal character will be converted to U+FFFD.

As a C++26 feature, it's not yet implemented so "implementation-defined" is unknown (but likely to be printable with `std::print`).

Final Notes

- Note 1: there also exists `.u8path()` to construct from a UTF-8 string in C++17, which is then deprecated in C++20.
  - Reason: C++20 introduces `char8_t`, which distinguishes UTF-8 sequence from `char` by template so there is no need to introduce a new method.
  - For the same reason, `.(generic_)u8string` returns `std::string` in C++17 and `std::u8string` in C++20.
- Note 2: to use `path` as key in map, you usually need to normalize it first by `canonical`.
  - Reason: comparison and hashing of `path` are performed **lexically** for the underlying components.
  - Without normalization, two equivalent paths may be seen as two keys.
  - On Windows, you may even need to `to_lower` all case-insensitive paths.
  - A more expensive but always-correct way is by `stdfs::equivalent` to compare, which needs file system call to check equality of two paths.

Covered later.