LECTURE 4

COMPILING

Historical compilers

- Proprietary
  - Intel C++ Compiler (ICC, 1970’s?)
  - Microsoft Visual C++ (MSVC, 1993)
  - ARM Compiler (ARMCC, 2005)
  - AMD Optimizing C/C++ Compiler (AOCC, 2017)
- Open source
  - GNU Compiler Collection (GCC, 1987)
  - LLVM (2003–)

Evolution of compilers

- 2014: ARM Compiler rebased on LLVM
- 2017: AMD Compiler was always based on LLVM
- 2021: Intel C++ Compiler rebased on LLVM

Current major compilers

- Microsoft Visual C++
  - default on MS Windows (in MS Visual Studio)
- GCC
  - default on most open source OSs
- LLVM (for C/C++: Clang)
  - base for hardware vendor (Intel, ARM, AMD, nVidia) compilers
  - default on MacOS, iOS (in Apple X Code)
  - default for native applications on Android

Components of a compiler

- Front-end (parses and analyses code – language-specific)
- Intermediate representation (IR) (most code optimization happens here)
- Back-end (writes assembly or machine code – ISA-specific)

- LLVM frontends:
  - C and C++ (Clang), Fortran (Flang), Rust, Zig, Swift
- LLVM backends:
  - Intel/AMD/ARM compilers, nVidia CUDA compiler, AMD ROCm

LLVM IR

```
define dso_local noundef i32 @square(int)(i32 noundef %num) #0 !dbg !10 {
entry:
  %num.addr = alloca i32, align 4
  store i32 %num, ptr %num.addr, align 4
  call void @llvm.dbg.declare(metadata ptr %num.addr, metadata !16, metadata !DIExpression()), !dbg !17
  %0 = load i32, ptr %num.addr, align 4, !dbg !18
  %1 = load i32, ptr %num.addr, align 4, !dbg !19
  %mul = mul nsw i32 %0, %1, !dbg !20
  ret i32 %mul, !dbg !21
}

declare void @llvm.dbg.declare(metadata, metadata, metadata) #1

attributes #0 = { mustprogress noinline nounwind optnone uwtable "frame-pointer"="all" "min-legal-vector-width"="0" "no-trapping-math"="true"
  "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cx8,+fxsr,+mmx,+sse,+sse2,+x87" "tune-cpu"="generic" }
attributes #1 = { nocallback nofree nosync nounwind speculatable willreturn memory(none) }
```

Compiler invocation (1)

- As usual, use `man gcc` / `man clang` for help.
- Compile and link:

```
gcc -o executable source_code.c
```

- Compile only:

```
gcc -c -o file.o file.c
```

- Link only

```
gcc -o executable file0.o file1.o file2.o file3.o
```

- Write assembly (see also:)

```
gcc -S assembly.S source_code.c
```

- Internally, `gcc` runs other tools (assembler: `as`, linker: `ld`)

Compiler invocation (2)

- Enable warnings:

```
gcc -Wall -c -o file.o file.c
```

- Enable optimization:

```
gcc -Wall -O3 -c -o file.o file.c
```

Note for MacOS

Install `binutils`:

- from MacPorts https://www.macports.org

  ```
  port install binutils
  ```

- or from Homebrew https://brew.sh/

  ```
  brew install binutils
  ```

Utilities may be prefixed by a g:

`objdump` → `gobjdump`

Tools

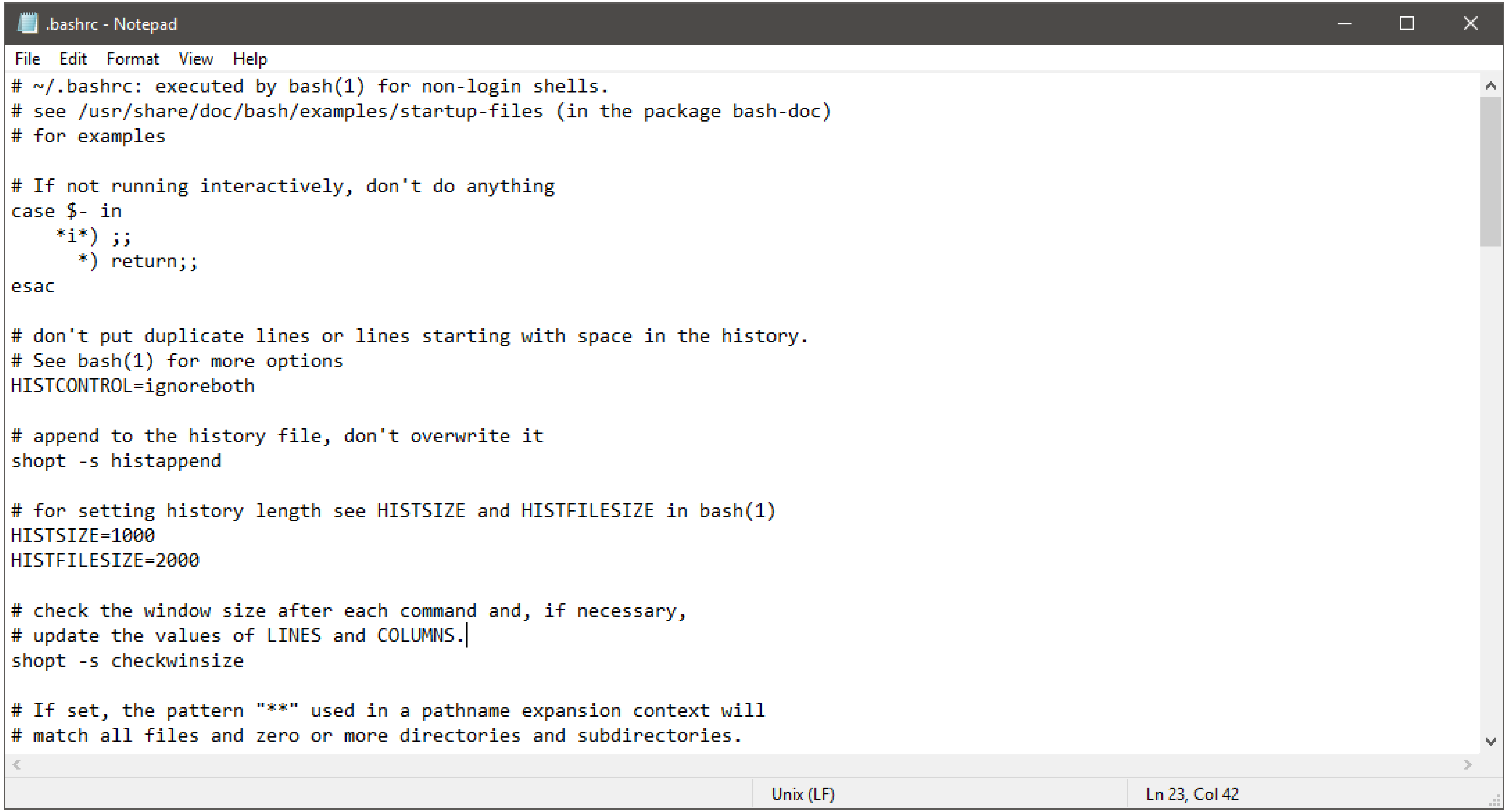
- `hexdump` dump hexadecimal representation of any file
  - `hexdump -C` also print ASCII for valid ASCII bytes
  - `hexdump -C | less` “pipe” outout to pager
  - `hexdump -C > file.hex` write outout to a file
- `readelf` print symbols in ELF object file
  - `readelf -a` print all object information
- `objdump` dump contents of object file
  - `objdump -M intel -d` disassembles object file, prints assembly code
  - `objdump -p` similar to `readelf`
- or online: http://godbolt.org

EDITING CODE

Applications for writing code

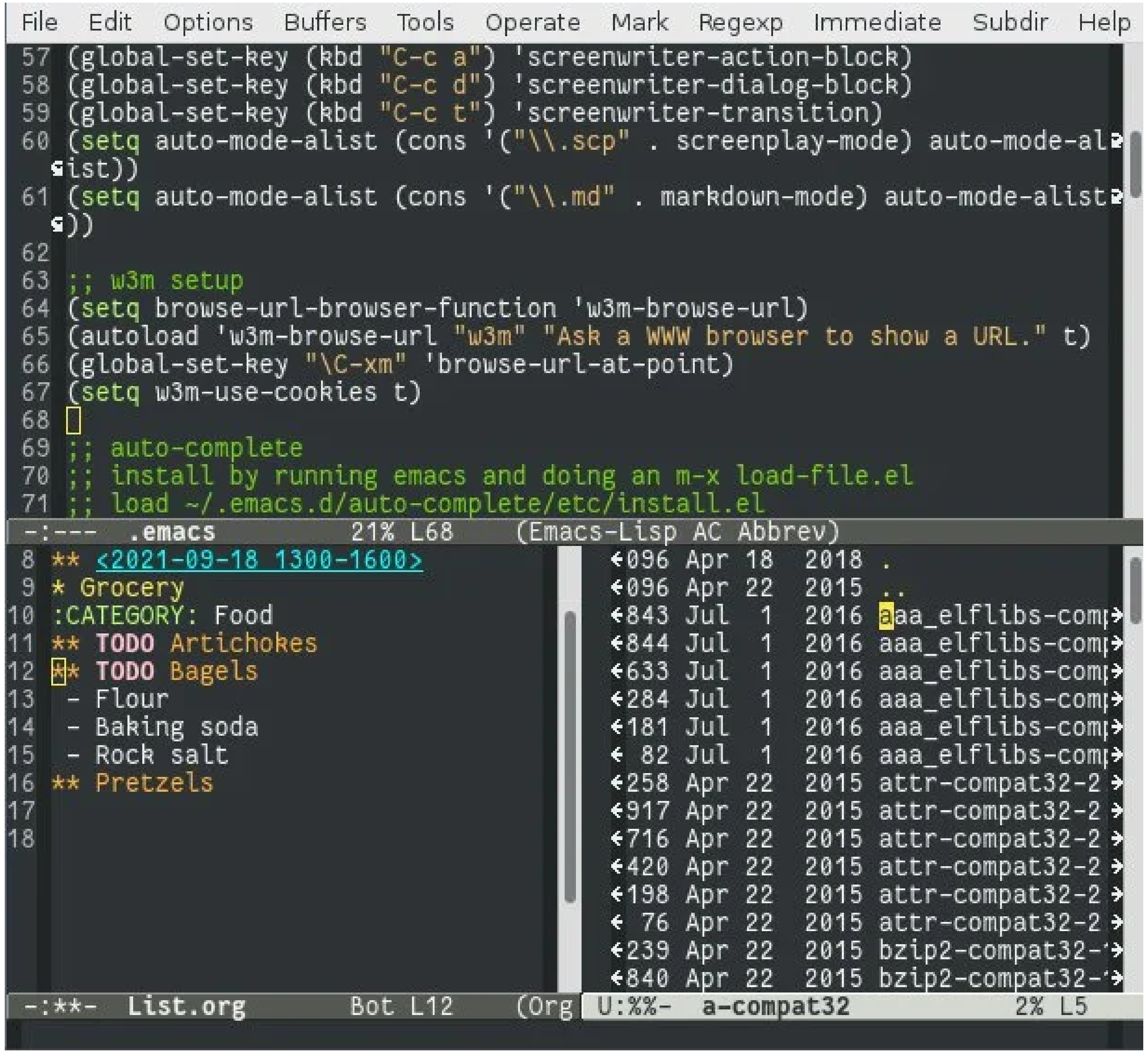
- Text editors
- Code editors
- Integrated development environment (IDE)

Text editor: Notepad



```
# ~/.bashrc: executed by bash(1) for non-login shells.
# see /usr/share/doc/bash/examples/startup-files (in the package bash-doc)
# for examples

# If not running interactively, don't do anything
case $- in
    *i*) ;;
      *) return;;
esac

# don't put duplicate lines or lines starting with space in the history.
# See bash(1) for more options
HISTCONTROL=ignoreboth

# append to the history file, don't overwrite it
shopt -s histappend

# for setting history length see HISTSIZE and HISTFILESIZE in bash(1)
HISTSIZE=1000
HISTFILESIZE=2000

# check the window size after each command and, if necessary,
# update the values of LINES and COLUMNS.
shopt -s checkwinsize

# If set, the pattern "**" used in a pathname expansion context will
# match all files and zero or more directories and subdirectories.
```

Code editor: emacs

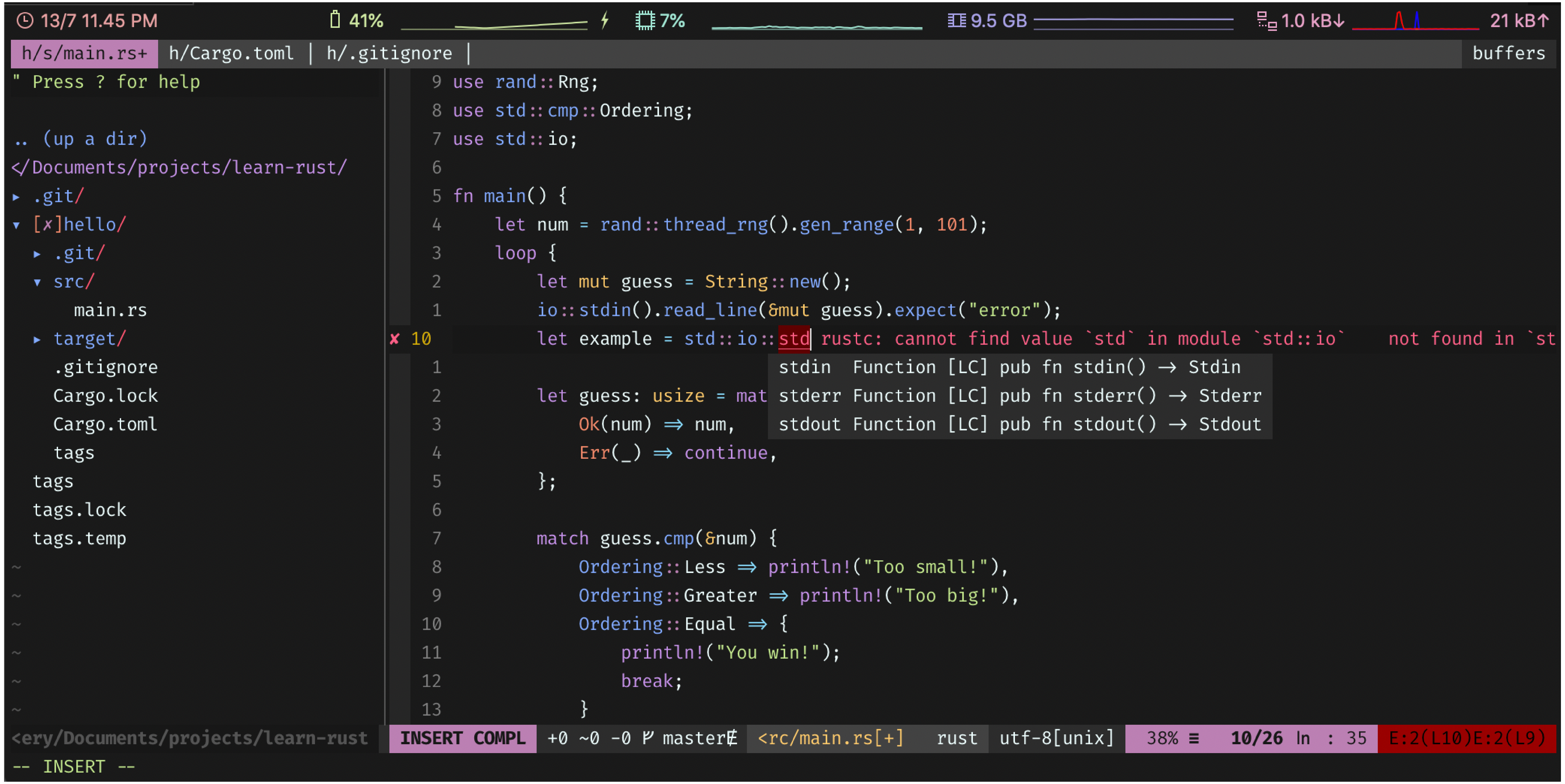


```
(global-set-key (kbd "C-c a") 'screenwriter-action-block)
(global-set-key (kbd "C-c d") 'screenwriter-dialog-block)
(global-set-key (kbd "C-c t") 'screenwriter-transition)
(setq auto-mode-alist (cons '("\\.scp" . screenplay-mode) auto-mode-alist))
(setq auto-mode-alist (cons '("\\.md" . markdown-mode) auto-mode-alist))

;; w3m setup
(setq browse-url-browser-function 'w3m-browse-url)
(autoload 'w3m-browse-url "w3m" "Ask a WWW browser to show a URL." t)
(global-set-key "\C-xm" 'browse-url-at-point)
(setq w3m-use-cookies t)

;; auto-complete
;; install by running emacs and doing an m-x load-file.el
;; load ~/.emacs.d/auto-complete/etc/install.el
-:---  .emacs          21% L68     (Emacs-Lisp AC Abbrev)
```

```
** <2021-09-18 1300-1600>
* Grocery
:CATEGORY: Food
** TODO Artichokes
** TODO Bagels
 - Flour
 - Baking soda
 - Rock salt
** Pretzels


-:**-  List.org        Bot L12     (Org
```

```
096 Apr 18  2018 .
096 Apr 22  2015 ..
843 Jul  1  2016 aaa_elflibs-com
844 Jul  1  2016 aaa_elflibs-com
633 Jul  1  2016 aaa_elflibs-com
284 Jul  1  2016 aaa_elflibs-com
181 Jul  1  2016 aaa_elflibs-com
 82 Jul  1  2016 aaa_elflibs-com
258 Apr 22  2015 attr-compat32-2
917 Apr 22  2015 attr-compat32-2
716 Apr 22  2015 attr-compat32-2
420 Apr 22  2015 attr-compat32-2
198 Apr 22  2015 attr-compat32-2
 76 Apr 22  2015 attr-compat32-2
239 Apr 22  2015 bzip2-compat32-
840 Apr 22  2015 bzip2-compat32-
U:%%-  a-compat32          2% L5
```

Code editor: vi / vim / neovim



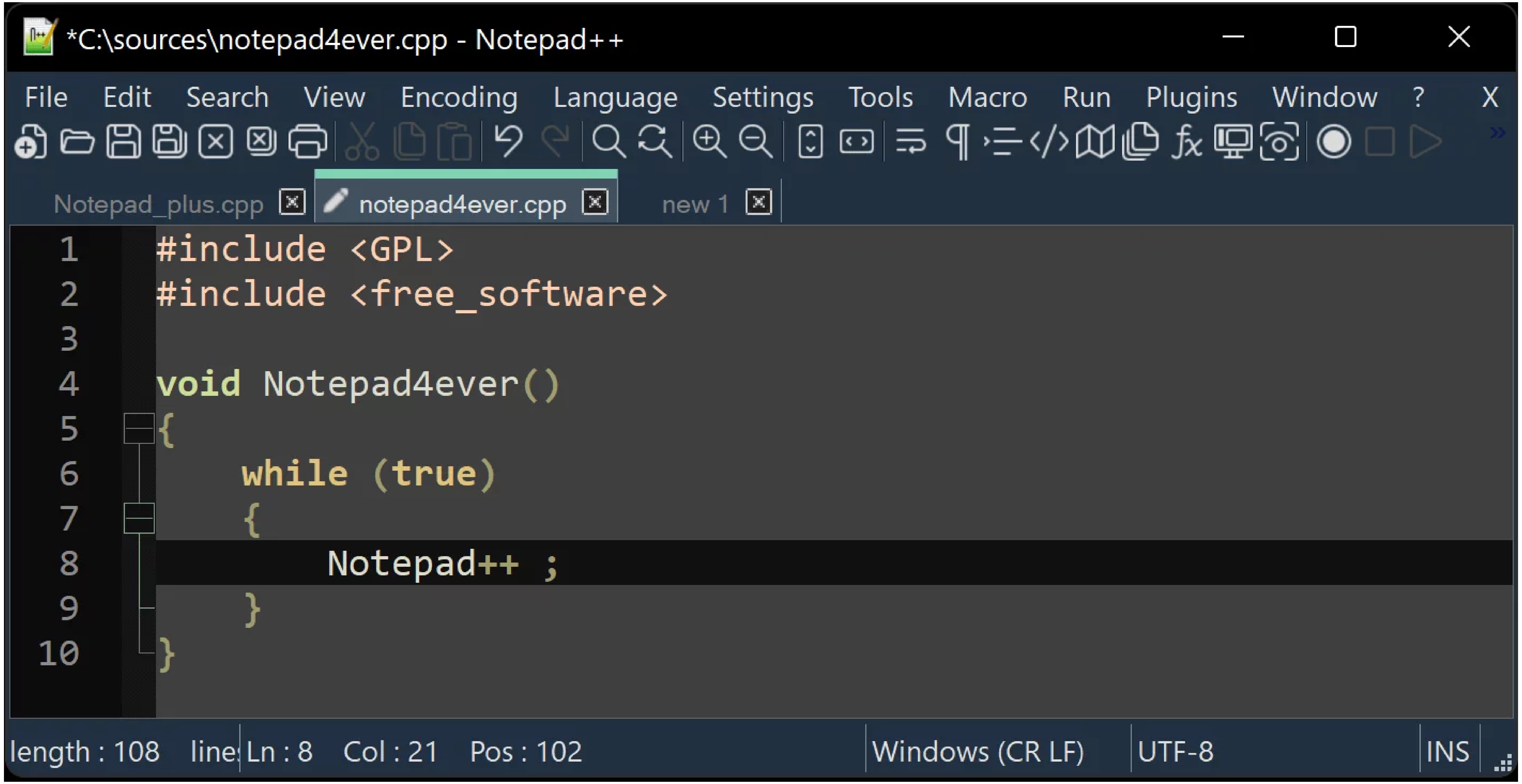
```
13/7 11.45 PM    41%    7%    9.5 GB    1.0 kB↓    21 kB↑
h/s/main.rs+  h/Cargo.toml | h/.gitignore |                                buffers
```

```
" Press ? for help

.. (up a dir)
</Documents/projects/learn-rust/
▸ .git/
▾ [✗]hello/
  ▸ .git/
  ▾ src/
      main.rs
  ▸ target/
    .gitignore
    Cargo.lock
    Cargo.toml
    tags
  tags
  tags.lock
  tags.temp
```

```
use rand::Rng;
use std::cmp::Ordering;
use std::io;

fn main() {
    let num = rand::thread_rng().gen_range(1, 101);
    loop {
        let mut guess = String::new();
        io::stdin().read_line(&mut guess).expect("error");
✘       let example = std::io::std rustc: cannot find value `std` in module `std::io`    not found in `st
                                  stdin  Function [LC] pub fn stdin() → Stdin
        let guess: usize = mat    stderr Function [LC] pub fn stderr() → Stderr
            Ok(num) ⇒ num,        stdout Function [LC] pub fn stdout() → Stdout
            Err(_) ⇒ continue,
        };

        match guess.cmp(&num) {
            Ordering::Less ⇒ println!("Too small!"),
            Ordering::Greater ⇒ println!("Too big!"),
            Ordering::Equal ⇒ {
                println!("You win!");
                break;
            }
```

```
<ery/Documents/projects/learn-rust  INSERT COMPL  +0 ~0 -0 ᚠ master⋕  <rc/main.rs[+]   rust  utf-8[unix]  38% ≡  10/26 ln : 35  E:2(L10)E:2(L9)
-- INSERT --
```

Code editor: Notepad++

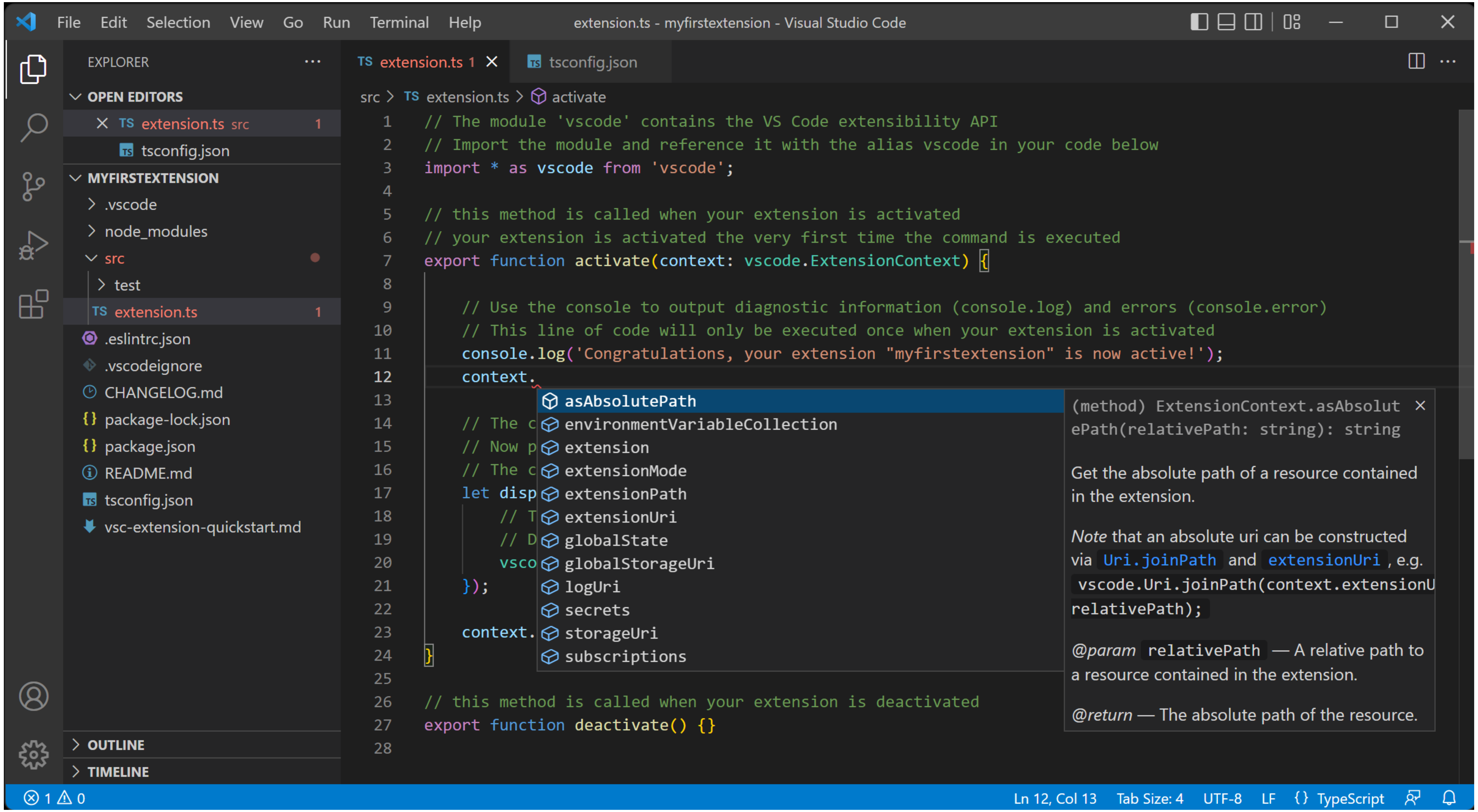


*C:\sources\notepad4ever.cpp - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ? X
Notepad_plus.cpp
notepad4ever.cpp
new 1

```
#include <GPL>
#include <free_software>

void Notepad4ever()
{
    while (true)
    {
        Notepad++ ;
    }
}
```

length : 108 line Ln : 8 Col : 21 Pos : 102 Windows (CR LF) UTF-8 INS

Code editor: Visual Studio Code



```
// The module 'vscode' contains the VS Code extensibility API
// Import the module and reference it with the alias vscode in your code below
import * as vscode from 'vscode';

// this method is called when your extension is activated
// your extension is activated the very first time the command is executed
export function activate(context: vscode.ExtensionContext) {

    // Use the console to output diagnostic information (console.log) and errors (console.error)
    // This line of code will only be executed once when your extension is activated
    console.log('Congratulations, your extension "myfirstextension" is now active!');
    context.

    // The c
    // Now p
    // The c
    let disp
        // T
        // D
        vsco
    });

    context.
}

// this method is called when your extension is deactivated
export function deactivate() {}
```

```
(method) ExtensionContext.asAbsolutePath(relativePath: string): string
```

Get the absolute path of a resource contained in the extension.

Note that an absolute uri can be constructed via `Uri.joinPath` and `extensionUri`, e.g. `vscode.Uri.joinPath(context.extensionUri, relativePath);`

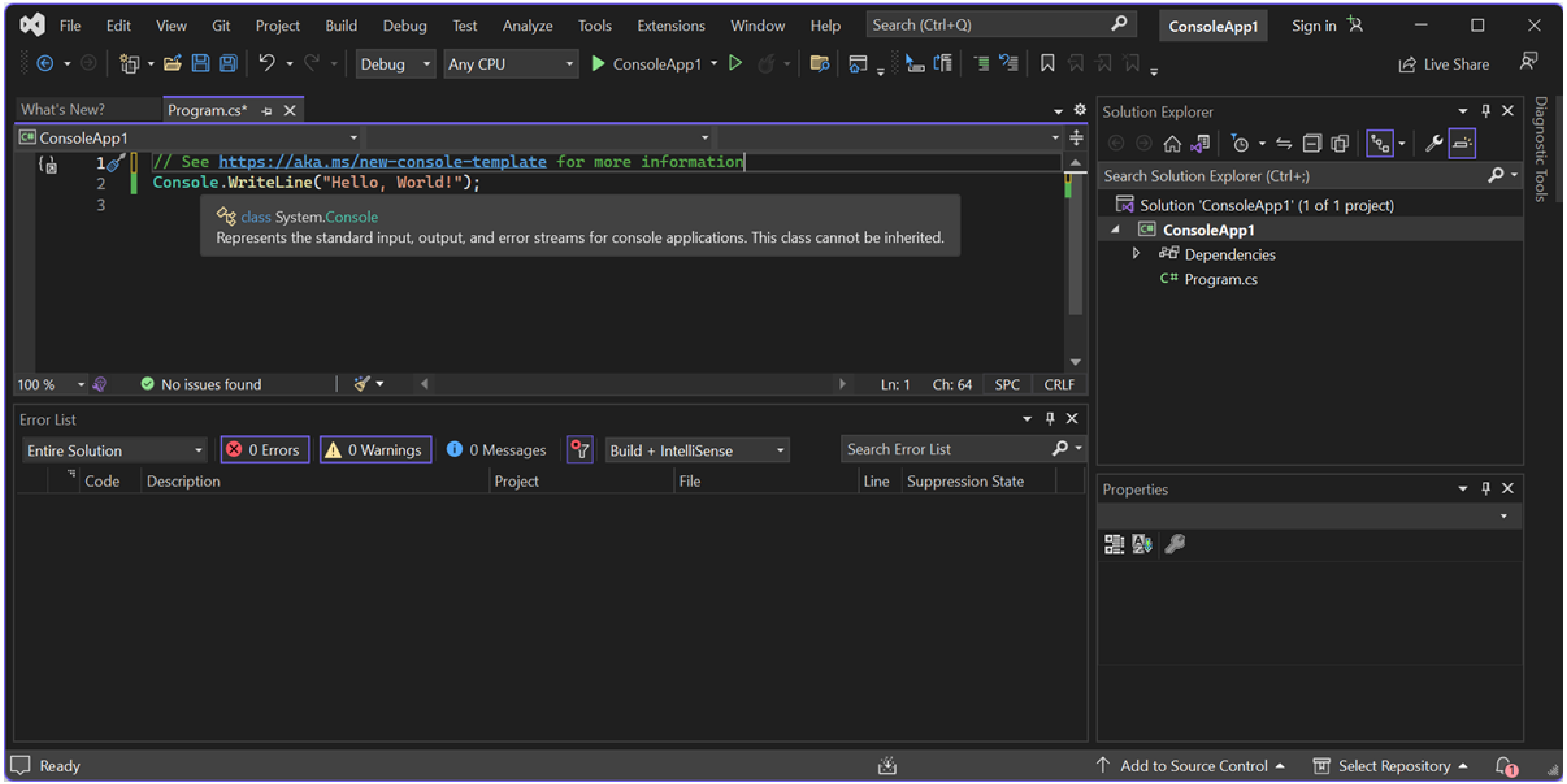
@param `relativePath` — A relative path to a resource contained in the extension.

@return — The absolute path of the resource.

More code editors

- gedit
- Kate
- Sublime Text (paid)
- many more…

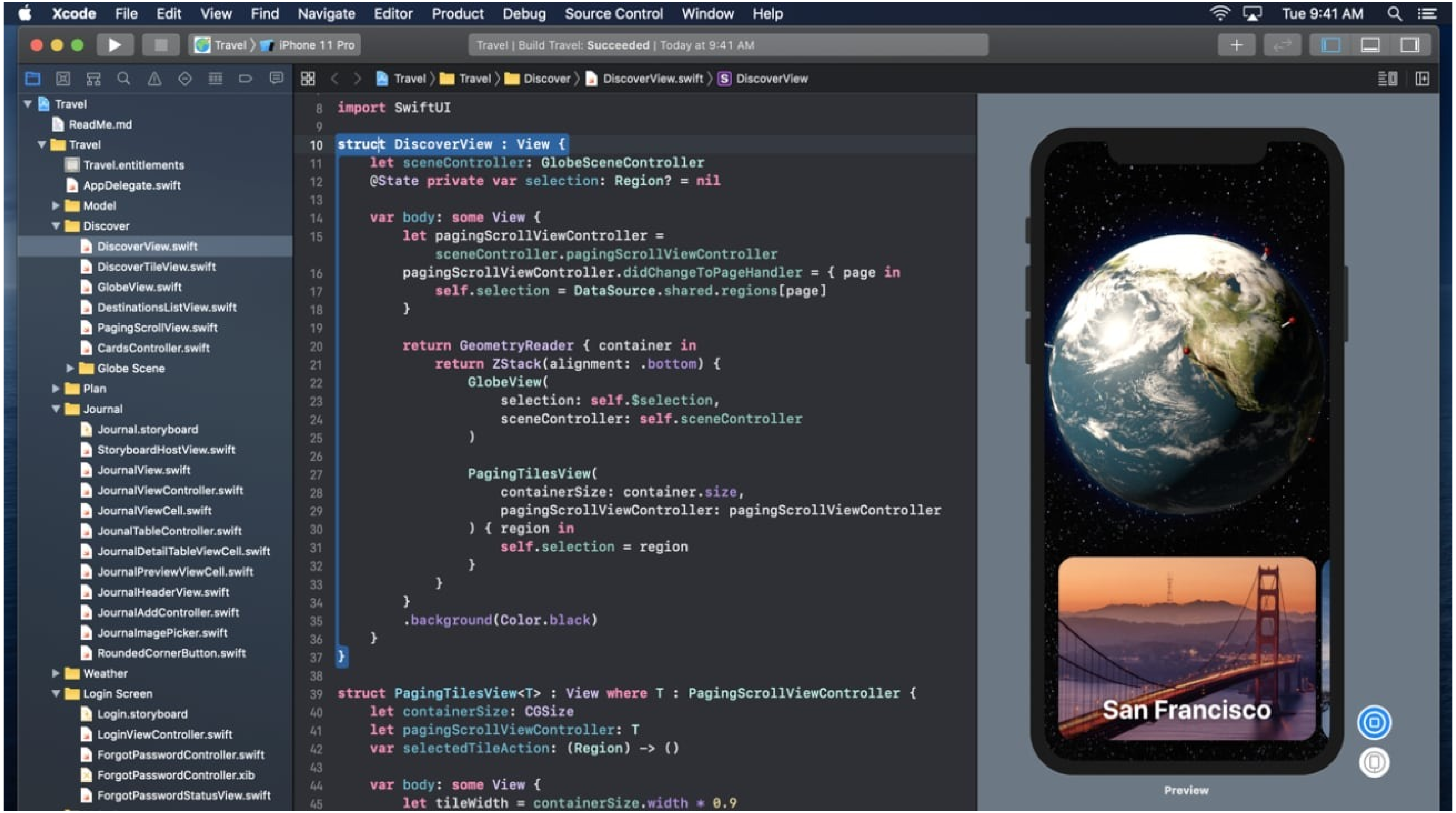
IDE: Microsoft Visual Studio (paid)



```
// See https://aka.ms/new-console-template for more information
Console.WriteLine("Hello, World!");

```

class System.Console
Represents the standard input, output, and error streams for console applications. This class cannot be inherited.

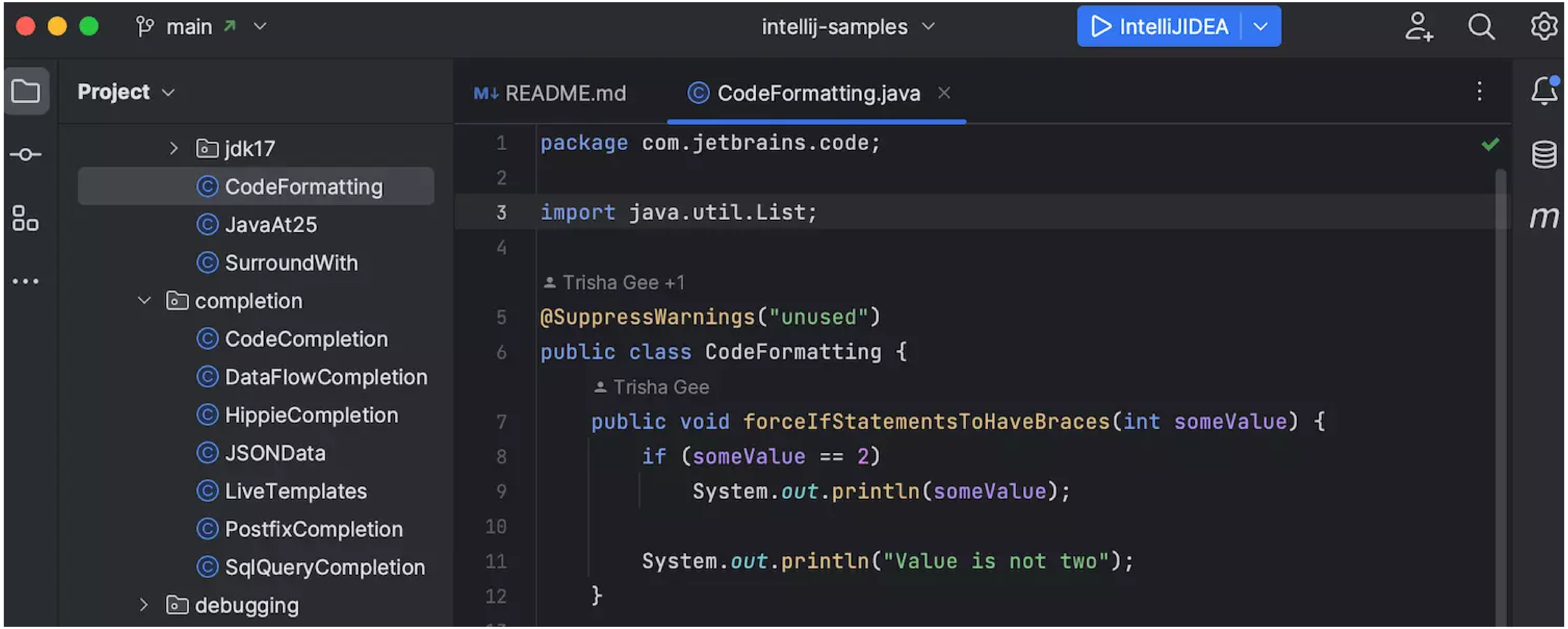
IDE: Apple Xcode



Travel | Build Travel: **Succeeded** | Today at 9:41 AM

```swift
import SwiftUI

struct DiscoverView : View {
    let sceneController: GlobeSceneController
    @State private var selection: Region? = nil

    var body: some View {
        let pagingScrollViewController =
            sceneController.pagingScrollViewController
        pagingScrollViewController.didChangeToPageHandler = { page in
            self.selection = DataSource.shared.regions[page]
        }

        return GeometryReader { container in
            return ZStack(alignment: .bottom) {
                GlobeView(
                    selection: self.$selection,
                    sceneController: self.sceneController
                )

                PagingTilesView(
                    containerSize: container.size,
                    pagingScrollViewController: pagingScrollViewController
                ) { region in
                    self.selection = region
                }
            }
        }
        .background(Color.black)
    }
}

struct PagingTilesView<T> : View where T : PagingScrollViewController {
    let containerSize: CGSize
    let pagingScrollViewController: T
    var selectedTileAction: (Region) -> ()

    var body: some View {
        let tileWidth = containerSize.width * 0.9
```

IDE: IntelliJ IDEA (paid)



```
package com.jetbrains.code;

import java.util.List;

@SuppressWarnings("unused")
public class CodeFormatting {
    public void forceIfStatementsToHaveBraces(int someValue) {
        if (someValue == 2)
            System.out.println(someValue);

        System.out.println("Value is not two");
    }
```

More IDEs

- PyCharm (Python, paid)
- Android Studio (paid)
- KDevelop
- QtCreator
- Dev-C++
- Spyder (Python)
- ...

Code editor vs. IDE

IDE pros:

- one-click compile
- IDE aware of whole project
    - can suggest code completions from different files
- integrated tools (e.g. debugger)

IDE cons:

- Project setup takes time and effort
- “Walled garden” problem
    - By default, anyone who wants to compile your project needs the same IDE.

BUILD SYSTEMS

How do we compile a complex project?

- Option 1:

```
gcc -Wall -O3 -c -o ggml.o ggml.c
gcc -Wall -O3 -c -o ggml-alloc.o ggml-alloc.c
g++ -Wall -O3 -c -o llama.o llama.cpp
g++ -Wall -O3 -c -o common.o common/common.c
g++ -Wall -O3 -c -o console.o common/console.c
g++ -Wall -O3 -c -o grammar-parser.o common/grammar-parser.c
g++ -Wall -O3 -shared -fPIC -o libllama.so ggml.o ggml-alloc.o llama.o \
                               common.o console.o grammar-parser.o
```

- Option 2
  - Put above commands in a “shell script” file, e.g. `compile.sh`
  - Run:

    ```
    ./compile.sh
    ```

  - Problems:
    - Difficult to modify (e.g. change compiler options)
    - We recompile everything everytime

Build automation

- IDE integrated:
    - Visual Studio
    - Xcode

- Stand-alone:
    - `make`
    - Bazel (based on Google's internal tool Blaze) / Buck (Facebook)
    - Ninja (Google, for Chrome)
    - CMake (uses `make`, Ninja,…), `qmake` (uses `make`), Meson (uses Ninja, …)

Make

- Create a file named `Makefile`:

```
ggml.o: ggml.c ggml.h ggml-cuda.h
        gcc -Wall -O3 -c -o ggml.o ggml.c

ggml-alloc.o: ggml-alloc.c ggml.h ggml-alloc.h
        gcc -Wall -O3 -c -o ggml-alloc.o ggml-alloc.c

llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h llama.h
        g++ -Wall -O3 -c -o llama.o llama.cpp

common.o: common/common.cpp common/common.h build-info.h common/log.h
        g++ -Wall -O3 -c -o common.o common/common.cpp

console.o: common/console.cpp common/console.h
        g++ -Wall -O3 -c -o console.o common/console.cpp

grammar-parser.o: common/grammar-parser.cpp common/grammar-parser.h
        g++ -Wall -O3 -c -o grammar-parser.o common/grammar-parser.cpp

libllama.so: ggml.o ggml-alloc.o llama.o common.o console.o grammar-parser.o
        g++ -Wall -O3 -shared -fPIC -o libllama.so ggml.o ggml-alloc.o llama.o \
                                       common.o console.o grammar-parser.o
```

- Run

```
make libllama.so
```

Make rule syntax

```
target: source0 source1 source2 ...
        recipe
```

Whenever one of the sources was modified after the target,
run the recipe (to rebuild the target).

Otherwise, consider target up-to-date and do nothing.

Make variables

```
CC := gcc
CXX := g++
CFLAGSS := -Wall -O3
CXXFLAGS := -Wall -O3

ggml.o: ggml.c ggml.h ggml-cuda.h
        $(CC) $(CFLAGS) -c -o ggml.o ggml.c

ggml-alloc.o: ggml-alloc.c ggml.h ggml-alloc.h
        $(CC) $(CFLAGS) -c -o ggml-alloc.o ggml-alloc.c

llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h llama.h
        $(CXX) $(CXXFLAGS) -c -o llama.o llama.cpp

common.o: common/common.cpp common/common.h build-info.h common/log.h
        $(CXX) $(CXXFLAGS) -c -o common.o common/common.cpp

console.o: common/console.cpp common/console.h
        $(CXX) $(CXXFLAGS) -c -o console.o common/console.cpp

grammar-parser.o: common/grammar-parser.cpp common/grammar-parser.h
        $(CXX) $(CXXFLAGS) -c -o grammar-parser.o common/grammar-parser.cpp

libllama.so: ggml.o ggml-alloc.o llama.o common.o console.o grammar-parser.o
        $(CXX) $(CXXFLAGS) -shared -fPIC -o libllama.so ggml.o ggml-alloc.o llama.o \
                                       common.o console.o grammar-parser.o
```

Special make variables

- `$(@)` the target of the current rule
- `$(<)` the first source of the current rule
- `$(^)` all the sources of the current rule

```
CC := gcc
CXX := g++
CFLAGSS := -Wall -O3
CXXFLAGS := -Wall -O3

ggml.o: ggml.c ggml.h ggml-cuda.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

ggml-alloc.o: ggml-alloc.c ggml.h ggml-alloc.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h llama.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

common.o: common/common.cpp common/common.h build-info.h common/log.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

console.o: common/console.cpp common/console.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

grammar-parser.o: common/grammar-parser.cpp common/grammar-parser.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

libllama.so: ggml.o ggml-alloc.o llama.o common.o console.o grammar-parser.o
        $(CXX) $(CXXFLAGS) -shared -fPIC -o $(@) $(^)
```

Static pattern rules

- Static pattern syntax:

```
target0 target1 target2 ... : target-pattern : source-pattern
        recipe
```

- Target pattern contains %, which will match anything
- Source pattern also contains %, which is replaced by the match in target
- Example:

```
some_file.o other_file.o third_file.o : %.o : %.c
        recipe
```

is equivalent to:

```
some_file.o: some_file.c
        recipe

other_file.o: other_file.c
        recipe

third_file.o: third_file.c
        recipe
```

```
ggml.o: ggml.c ggml.h ggml-cuda.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

ggml-alloc.o: ggml-alloc.c ggml.h ggml-alloc.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)
```

becomes

```
ggml.o ggml-alloc.o: %.o: %.c %.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

ggml.o: ggml-cuda.h # Additional sources
ggml-alloc.o: ggml.h # Additional sources
```

```
CC := gcc
CXX := g++
CFLAGSS := -Wall -O3
CXXFLAGS := -Wall -O3

ggml.o ggml-alloc.o: %.o: %.c %.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

ggml.o: ggml-cuda.h # Additional sources
ggml-alloc.o: ggml.h # Additional sources

llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h llama.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

common.o console.o grammar-parser.o: %.o: common/%.cpp common/%.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

common.o: build-info.h common/log.h # Additional sources

libllama.so: ggml.o ggml-alloc.o llama.o common.o console.o grammar-parser.o
        $(CXX) $(CXXFLAGS) -shared -fPIC -o $(@) $(^)
```

```makefile
CC := gcc
CXX := g++
CFLAGSS := -Wall -O3
CXXFLAGS := -Wall -O3

COBJS := ggml.o ggml-alloc.o
CXXOBJS_LLAMA := llama.o
CXXOBJS_COMMON := common.o console.o grammar-parser.o
CXXOBJS := $(CXXOBJS_LLAMA) $(CXXOBJS_COMMON)

# Build rules
$(COBJS): %.o: %.c %.h
        $(CC) $(CFLAGS) -c -o $(@) $(<)

$(CXXOBJS_LLAMA): %.o: %.cpp %.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

$(CXXOBJS_COMMON): %.o: common/%.cpp common/%.h
        $(CXX) $(CXXFLAGS) -c -o $(@) $(<)

libllama.so: $(COBJS) $(CXXOBJS)
        $(CXX) $(CXXFLAGS) -shared -fPIC -o $(@) $(^)

# Additional sources
ggml.o: ggml-cuda.h
ggml-alloc.o: ggml.h
llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h
common.o: build-info.h common/log.h
```

Phony and default targets

- A “phony” target does not necessarily correspond to a file name:

```
.PHONY: clean

clean:
	rm libllama.so
```

- If no target is provided to the `make` command, the default target is the first one. A common pattern is:

```
.PHONY: default

default: libllama.so
```

```
CC := gcc
CXX := g++
CFLAGSS := -Wall -O3
CXXFLAGS := -Wall -O3

COBJS := ggml.o ggml-alloc.o
CXXOBJS_LLAMA := llama.o
CXXOBJS_COMMON := common.o console.o grammar-parser.o
CXXOBJS := $(CXXOBJS_LLAMA) $(CXXOBJS_COMMON)
LIBTARGET := libllama.so

.PHONY: default clean

# Build rules
default: $(LIBTARGET)

clean:
	rm -f $(COBJS) $(CXXOBJS) $(LIBTARGET)

$(COBJS): %.o: %.c %.h
	$(CC) $(CFLAGS) -c -o $(@) $(<)

$(CXXOBJS_LLAMA): %.o: %.cpp %.h
	$(CXX) $(CXXFLAGS) -c -o $(@) $(<)

$(CXXOBJS_COMMON): %.o: common/%.cpp common/%.h
	$(CXX) $(CXXFLAGS) -c -o $(@) $(<)

$(LIBTARGET): $(COBJS) $(CXXOBJS)
	$(CXX) $(CXXFLAGS) -shared -fPIC -o $(@) $(^)

# Additional sources
ggml.o: ggml-cuda.h
ggml-alloc.o: ggml.h
llama.o: llama.cpp ggml.h ggml-alloc.h ggml-cuda.h ggml-metal.h
common.o: build-info.h common/log.h
```

Using shell commands

- The syntax is:

```
$(shell any-shell-command)
```

- For example:

```
TODAY := $(shell date)
C_FILES := $(shell ls *.c)
```

String replacement in variables

- The syntax is:

```
$(variable:pattern=replacement)
```

- The pattern contains %, which will match any substring
- The replacement may contain %, which will be replaced by the matched substring
- For example:

```
C_FILES := $(shell ls *.c)
O_FILES := $(C_FILES:%.c=%.o)
```

For more about make

```
# Using make
man make

# Writing Makefiles
info make
```