Compilers 101

Compiler frontend.
Working with AST and static analysis

Previously…

Preprocessing

Lexical analysis

Syntax analysis

Semantic analysis

IR Generation

IR Optimization

Optimization

Code generation

Frontend

Middle-end

Backend

Today

- Static analysis and its use cases
- Control-flow graphs
- Practical usage of Clang framework

What is static analysis?

- Static analysis is the analysis of software without executing any program code

Why static analysis?

- Reduce number of bugs
  - Some bugs are hard to find, e.g., = vs ==
- Legal obligations
  - Safety critical code must pass certifications
- Code Quality Improvement, efficiency and automation
- Education
- Basically, any rule enforcement

Warnings

- The most basic kind of static analysis
  - Missing return statement, missing case in switch, use of deprecated functions
- Built into compiler
- BKM: always enable `-Wall (-Wextra) -Werror` flags (or analogs) for your project

Linters

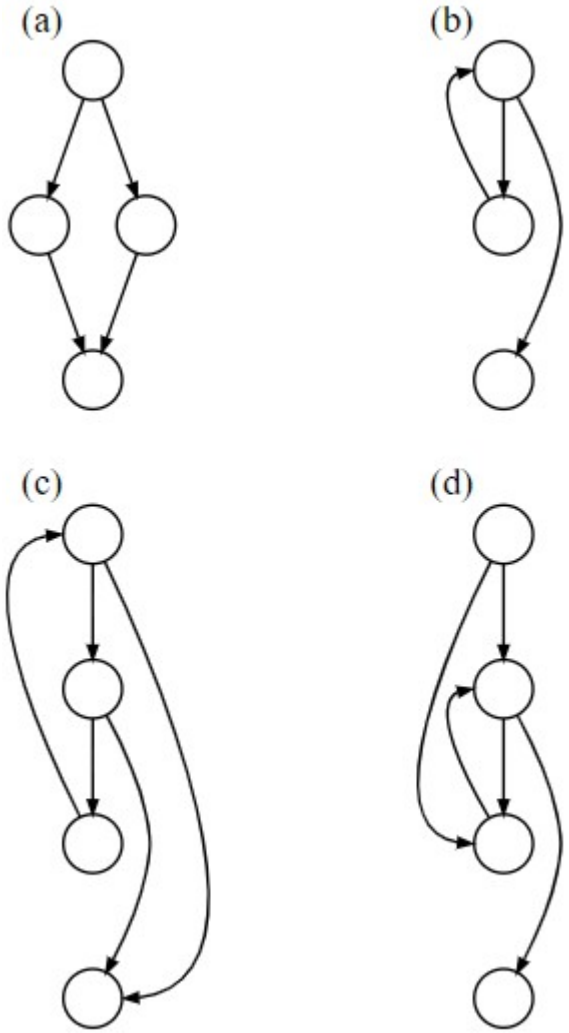
- Checks that your code follows some rules
  - Google Code Style rules
  - C++ core guidelines
- Those checks are not necessarily related to program functionality
  - Often highly opinionated

Static analyzers

- The most advanced static analyzers can perform data flow analysis and provide correctness checks
- Examples:
- clang static analyzer
- cppcheck
- PVS Studio

Control-flow graphs

- A control-flow graph is a representation of all paths that might be traversed through a program during execution



- Source: https://en.wikipedia.org/wiki/Control-flow_graph

CFG demo

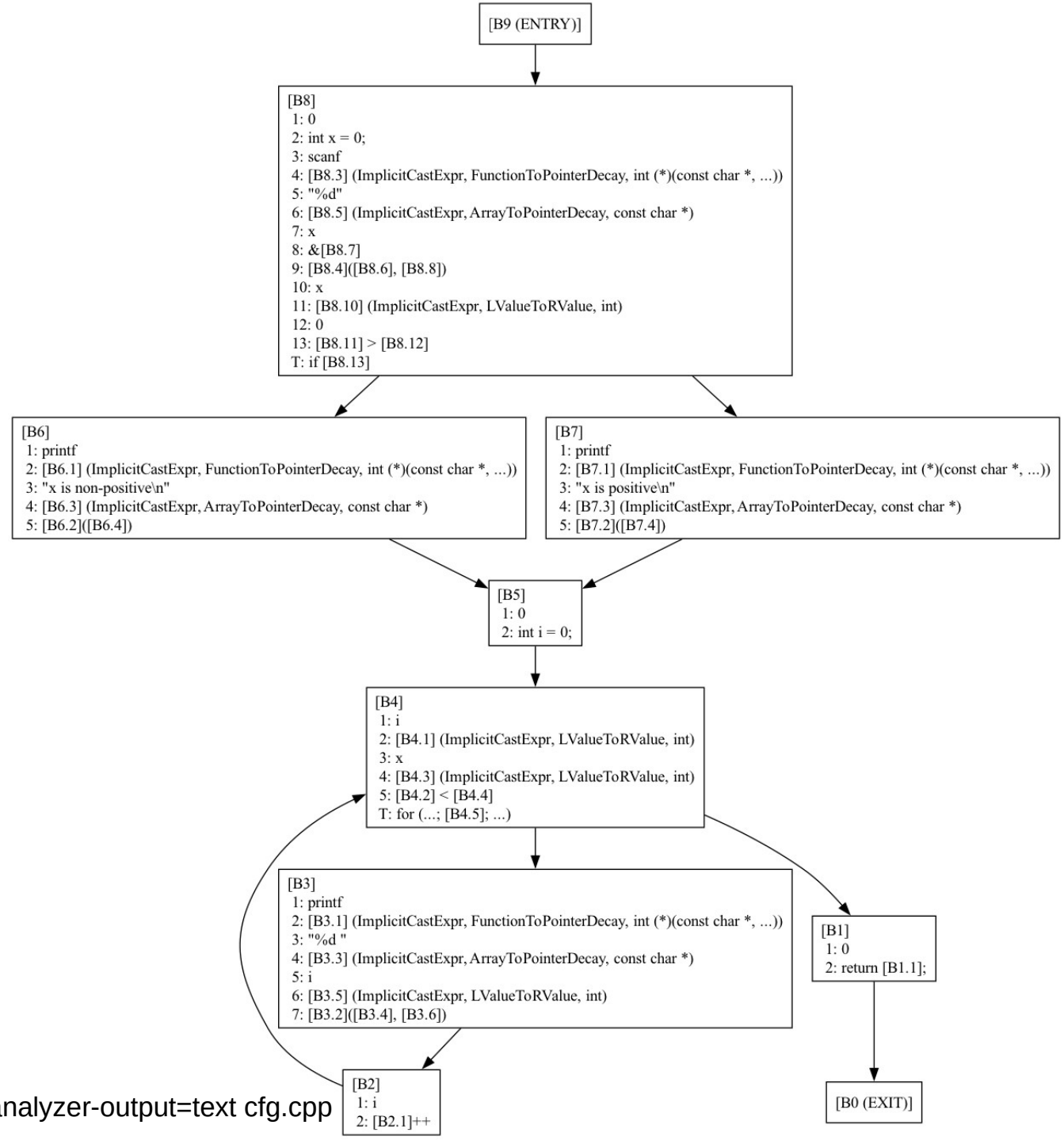
```c
#include <stdio.h>

int main() {
    int x = 0;
    scanf("%d", &x);

    if (x > 0) {
        printf("x is positive\n");
    } else {
        printf("x is non-positive\n");
    }

    for (int i = 0; i < x; i++) {
        printf("%d ", i);
    }

    return 0;
}
```



clang -Xclang -analyze -Xclang -analyzer-checker=debug.ViewCFG -Xclang -analyzer-output=text cfg.cpp

Dominators

- A block M dominates block N if every path from the entry that reaches block N must pass through block M
- Block M postdomintates block N if every path from N to exit must pass through M

Dominator trees

- Data structure depicting the dominator relationships
- Lengauer-Tarjan algorithm (O(nlogn))
- See more: https://www.llvm.org/devmtg/2017-10/slides/Kuderski-Dominator_Trees.pdf

Dominator tree (example)

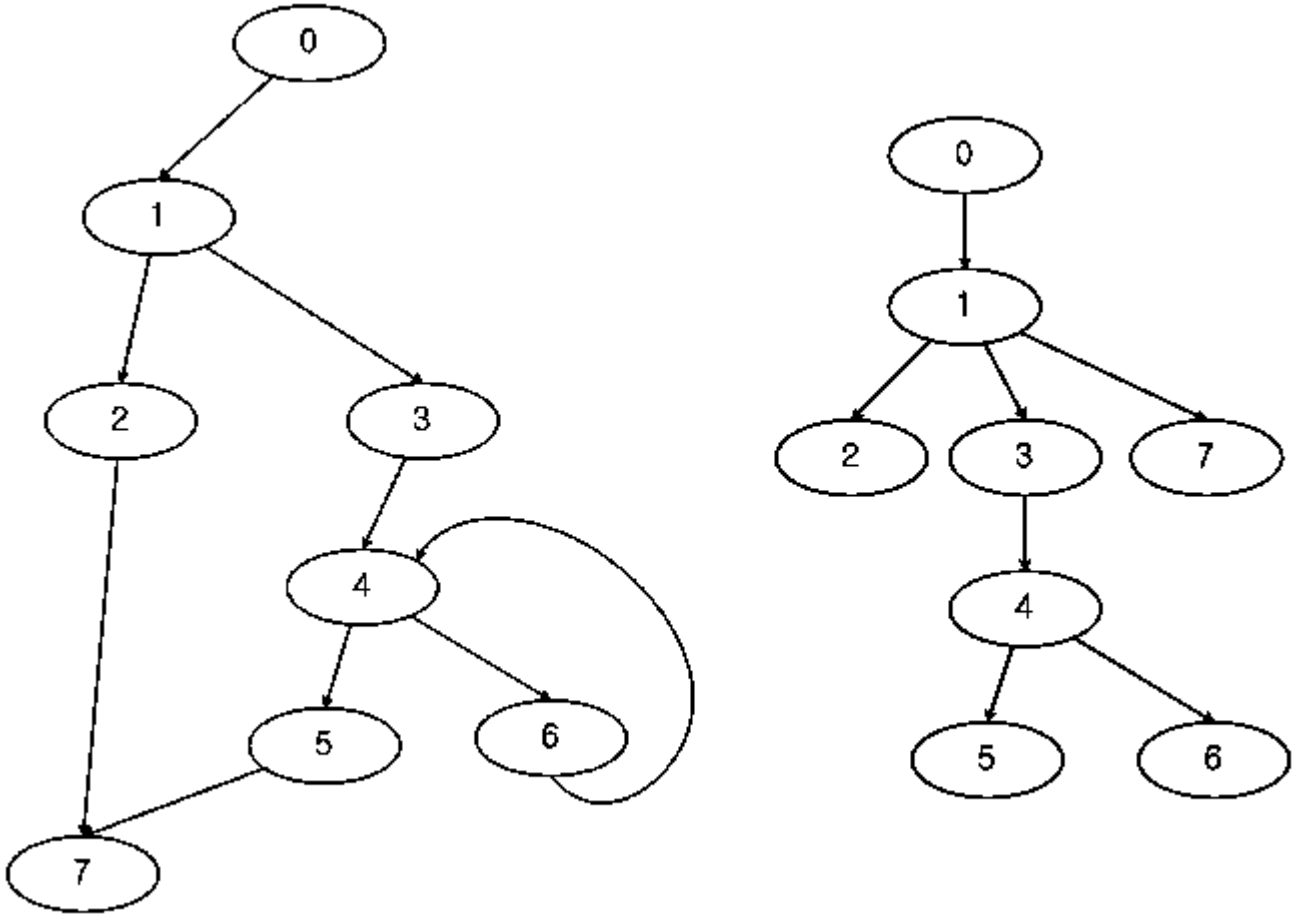


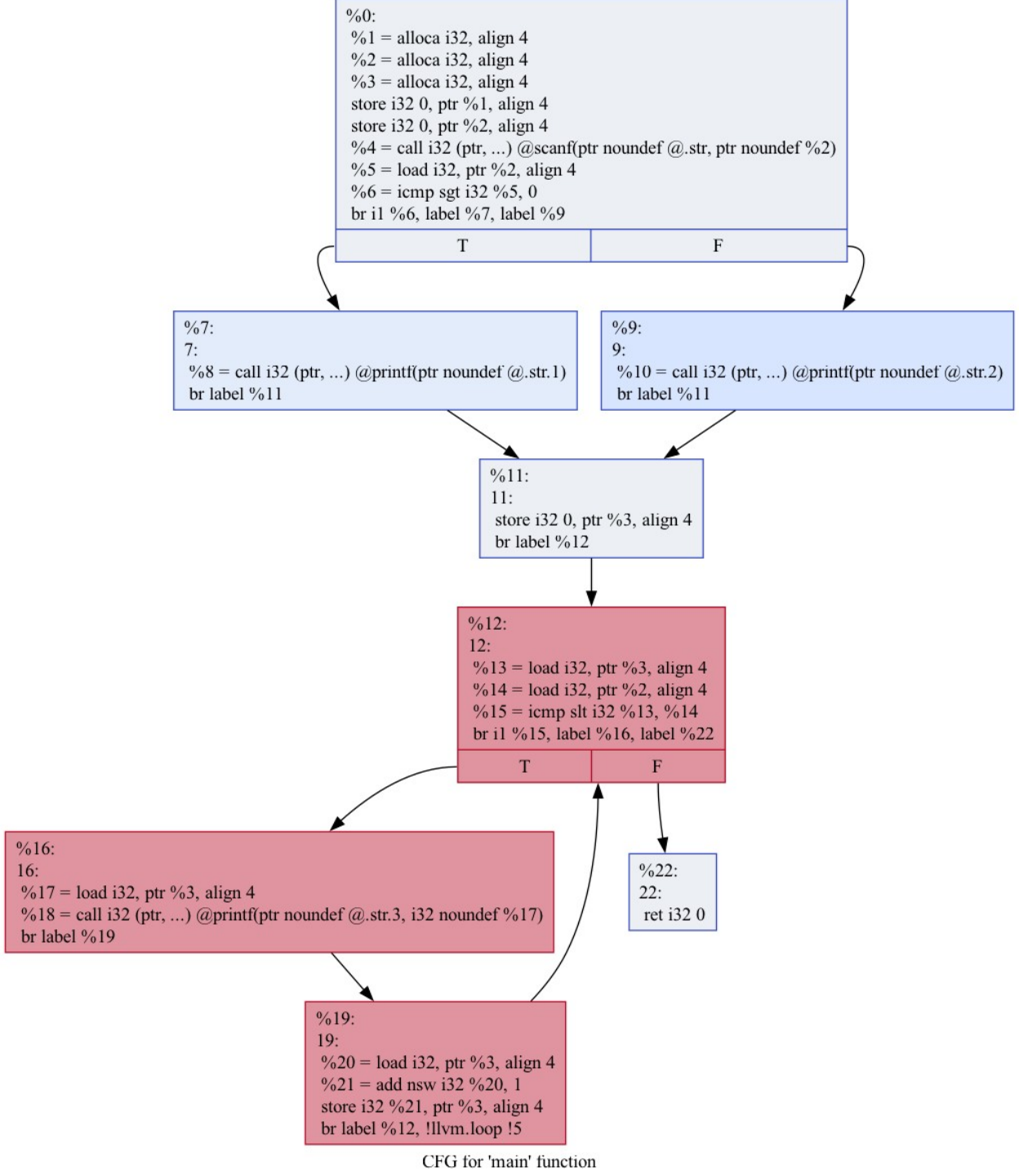
Figure 1: An example graph and its dominator tree.

Source: https://www.boost.org/doc/libs/1_85_0/libs/graph/doc/lengauer_tarjan_dominator.htm

Dominator trees (demo)

How to build:

```
clang -S -emit-llvm dominator.cpp -o dominator.ll
opt -passes='dot-cfg' dominator.ll
dot -Tpng .main.dot -o main.png
```



Hacking on Clang

- LibTooling – interface to write standalone tools based on clang
- LibFormat – library for automatic source code formatting
- LibClang – stable C interface for Clang
- Clang Plugins – do extra actions during compilation
- More on that:
https://clang.llvm.org/docs/index.html#using-clang-as-a-library

Working with AST

- AST is a graph, and you can use any graph theory algorithms
- Examining AST: -Xclang -ast-dump -fsyntax-only
- Clang framework provides a few helpers to work with AST
  - ASTConsumer
  - RecursiveASTVisitor
  - ASTAction
- More on that: https://www.youtube.com/watch?v=VqCkCDFLSsc

RecursiveASTVisitor

- CRTP class
- Provides methods to act on certain AST node classes
- Basically, an implementation of DFS

```
class FindNamedClassVisitor
  : public RecursiveASTVisitor<FindNamedClassVisitor> {
public:
  explicit FindNamedClassVisitor(ASTContext *Context)
    : Context(Context) {}

  bool VisitCXXRecordDecl(CXXRecordDecl *Declaration) {
    if (Declaration->getQualifiedNameAsString() == "n::m::C") {
      FullSourceLoc FullLocation = Context->getFullLoc(Declaration->getBeginLoc());
      if (FullLocation.isValid())
        llvm::outs() << "Found declaration at "
                     << FullLocation.getSpellingLineNumber() << ":"
                     << FullLocation.getSpellingColumnNumber() << "\n";
    }
    return true;
  }

private:
  ASTContext *Context;
};
```

LLVM IR generation

Typical use case for AST node visitors. Also can be referred as CodeGen, but do not confuse with LLVM CodeGen

- Uses AST visitors, IRBuilder, and TargetInfo classes
- CodeGenModule class keeps global state, e.g. LLVM type cache. Emits global and some shared entities.
- CodeGenFunction class keeps per function state. Emits LLVM IR for function body statements.

- The output can be inspected using the -emit-llvm (to force -S for textual representation) option to clang. You can also use -emit-llvm-bc to write an LLVM bitcode file which can be processed by the suite of LLVM tools like llvm-dis, llvm-nm, etc.

ASTConsumer

- An interface used to write generic actions on AST
- Provides many different entry points

```
class FindNamedClassConsumer : public clang::ASTConsumer {
public:
  virtual void HandleTranslationUnit(clang::ASTContext &Context) {
    // Traversing the translation unit decl via a RecursiveASTVisitor
    // will visit all nodes in the AST.
    Visitor.TraverseDecl(Context.getTranslationUnitDecl());
  }
private:
  // A RecursiveASTVisitor implementation.
  FindNamedClassVisitor Visitor;
};
```

FrontendAction

- FrontendActions are entry points for Clang-based tools (including Clang compiler)

```
class FindNamedClassAction : public clang::ASTFrontendAction {
public:
  virtual std::unique_ptr<clang::ASTConsumer> CreateASTConsumer(
    clang::CompilerInstance &Compiler, llvm::StringRef InFile) {
    return std::make_unique<FindNamedClassConsumer>(&Compiler.getASTContext());
  }
};
```

Source manager

- Source location
file:line:col

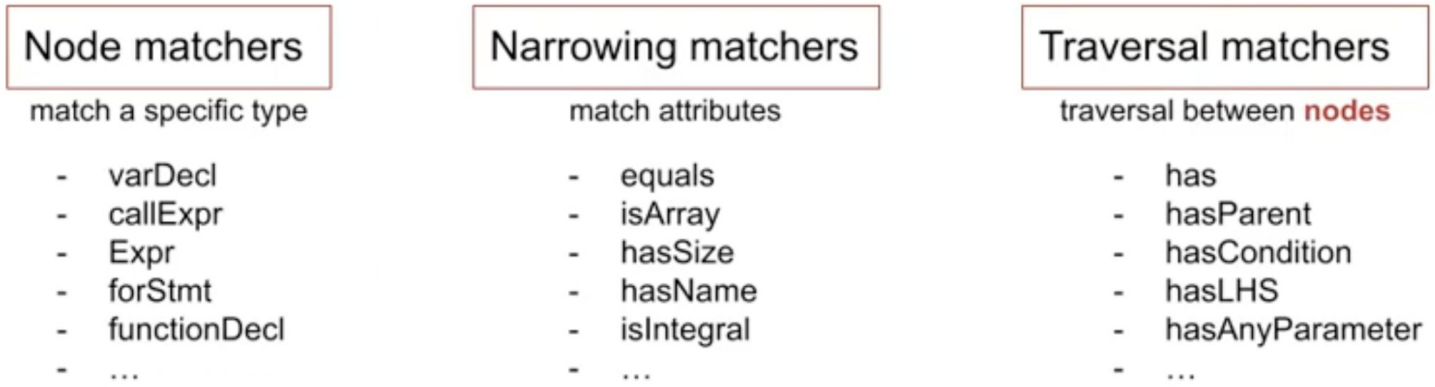
- AST does not contain information on source locations
  - It may be required for code re-writing
- SourceManager is owned by ASTContext:

```
FullSourceLoc FullLocation = Context->getFullLoc(Declaration->getBeginLoc());
```

- More info: https://clang.llvm.org/docs/RAVFrontendAction.html

Matching AST

- Sometimes there's a need to find certain patterns in AST
- Clang provides matchers interface:
  - Node matchers – find specific node type
  - Narrowing matchers – match attributes on AST nodes
  - Traversal matchers – traversal between AST nodes
- More info on syntax: https://clang.llvm.org/docs/LibASTMatchersReference.html#decl-matchers



Clang Transformer

- Framework for writing C++ diagnostics and source transformations
- Built on Matchers interface and LibTooling
- Rule examples:

```
makeRule(functionDecl(hasName("MkX").bind("fun"),
         noopEdit(node("fun")),
         cat("The name ``MkX`` is not allowed for functions; please rename"));
```

```
makeRule(declRefExpr(to(functionDecl(hasName("MkX")))),
         changeTo(cat("MakeX")),
         cat("MkX has been renamed MakeX"));
```

clang-tidy

- Clang-based linter tool
- Provides rules for many standards, including:
  - C++ core guidelines
  - Abseil
  - Google
  - CERT
  - Linux Kernel
  - LLVM

Extending clang-tidy

- Most useful source of knowledge: look at existing code
- Example (https://github.com/llvm/llvm-project/blob/main/clang-tools-extra/clang-tidy/llvm/):

```
/// Looks for local `Twine` variables which are prone to use after frees and
/// should be generally avoided.
class TwineLocalCheck : public ClangTidyCheck {
public:
  TwineLocalCheck(StringRef Name, ClangTidyContext *Context)
      : ClangTidyCheck(Name, Context) {}
  void registerMatchers(ast_matchers::MatchFinder *Finder) override;
  void check(const ast_matchers::MatchFinder::MatchResult &Result) override;
};
```

```
void TwineLocalCheck::registerMatchers(MatchFinder *Finder) {
  auto TwineType =
      qualType(hasDeclaration(cxxRecordDecl(hasName("::llvm::Twine"))));
  Finder->addMatcher(
      varDecl(unless(parmVarDecl()), hasType(TwineType)).bind("variable"),
      this);
}
```

Case study: modularize

- modularize is a standalone tool that checks whether a set of headers provides the consistent definitions required to use modules

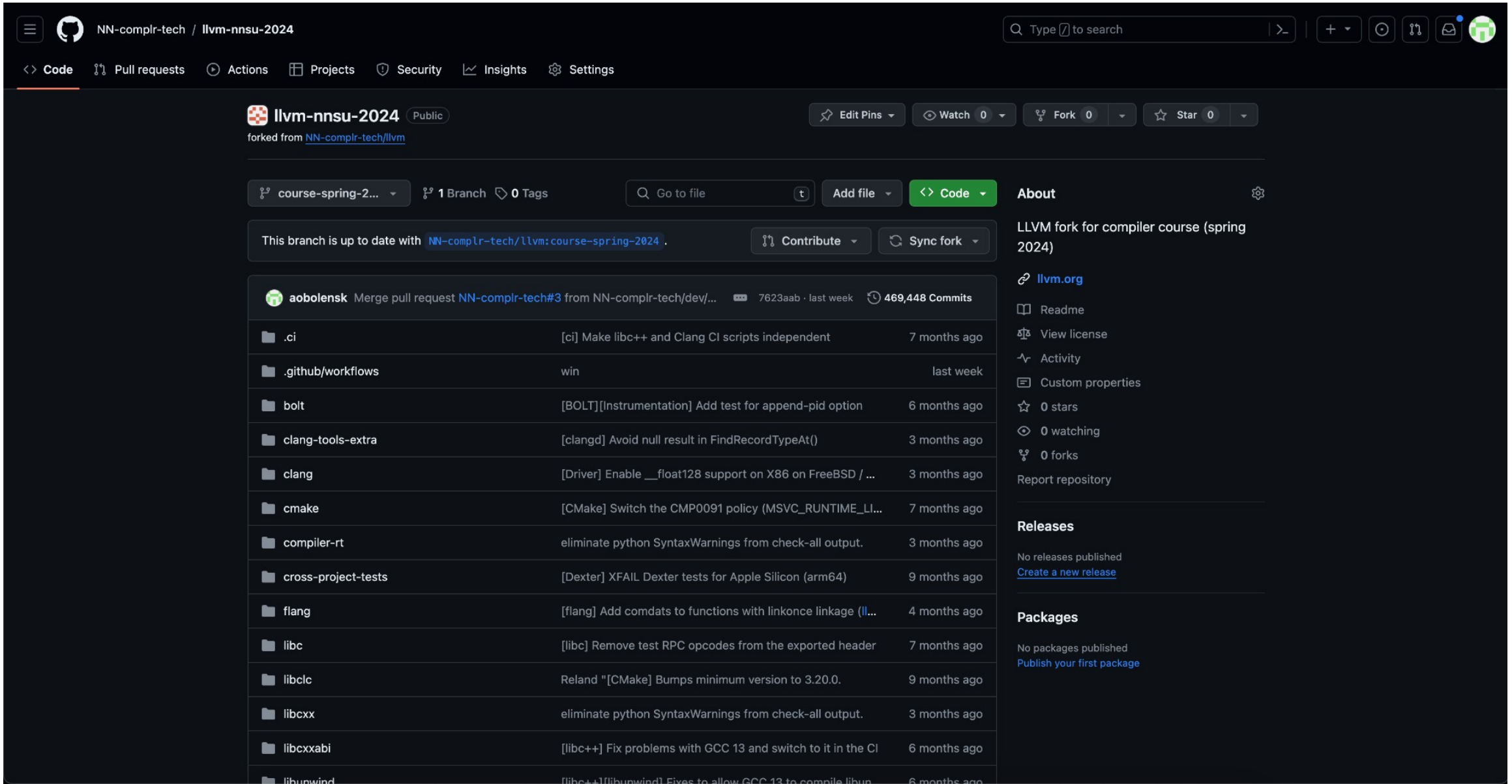
```
 (...)/SubHeader.h:11:5:
#if SYMBOL == 1
    ^
error: Macro instance 'SYMBOL' has different values in this header,
       depending on how it was included.
  'SYMBOL' expanded to: '1' with respect to these inclusion paths:
    (...)/Header1.h
      (...)/SubHeader.h
(...)/SubHeader.h:3:9:
#define SYMBOL 1
        ^
Macro defined here.
  'SYMBOL' expanded to: '2' with respect to these inclusion paths:
    (...)/Header2.h
        (...)/SubHeader.h
(...)/SubHeader.h:7:9:
#define SYMBOL 2
        ^
Macro defined here.
```

Case study: C++ core guidelines

- C++ Core Guidelines provide helper types for memory management
  - gsl::owner<…>
  - gsl::not_null<…>
- clang-tidy will warn if you’re not using any of these and to suspicious things
  - https://clang.llvm.org/extra/clang-tidy/checks/cppcoreguidelines/owning-memory.html

Hands-on

https://github.com/NN-complr-tech/compiler-course-2025



Lab assignment #1

- Write a simple Clang AST plugin

- Task list in Google Docs
- Deadline: March, 19
- Where to seek help

- https://clang.llvm.org/docs/ClangPlugins.html
- https://github.com/llvm/llvm-project/tree/main/clang/examples/PrintFunctionNames

- Contact teachers

Acceptance criterias

- The code base with implementation passes clang-format/clang-tidy checks on CI
- The code base with implementation passes build and test stage on CI
- LIT tests are added and passed on CI

FileCheck

- Tool from clang toolchain
- It is widely used for testing in LLVM framework

- How to run FileCheck tool:
  - FileCheck %s - compare stdin with file %s
- string to be verified:
  - CHECK: content
- Manual: https://llvm.org/docs/CommandGuide/FileCheck.html
- Run LIT test:
  - llvm-lit path/to/test

llvm-lit

lit is a portable tool for executing LLVM and Clang style test suites, summarizing their results, and providing indication of failures. lit is designed to be a lightweight testing tool with as simple a user interface as possible.

Manual: https://llvm.org/docs/CommandGuide/lit.html

llvm-lit simple test demo

clang > test > CodeGen > _demo > C++ 1.cpp > ...

```
1  // RUN: %clangxx %s -emit-llvm -c -S -o - | FileCheck %s
2  #include <iostream>
3
4
5  // CHECK: define noundef i32 @main() #0
6  int main() {
7      return 0;
8  }
```

$PATH_TO_LLVM_BIN/llvm-lit -a clang/test/_demo/1.cpp

Next time…

- Intermediate representations
- LLVM IR
- IR generation

Test

https://forms.gle/KedxuyGUAkYiMmYf6

Для каких целей используется построение графов (control flow graph и dominator tree) в clang?

Your answer

Зачем нужен статический анализ? Где он используется?

Your answer

Как статический анализ связан с компилятором?

Your answer

Backup: me@gooddoog.ru

Extra materials

- Data flow analysis - https://www.youtube.com/watch?v=OROXJ9-wUQE
- AST Matchers:
  - https://github.com/lac-dcc/llvm-course/tree/master/ast-matcher
  - https://www.youtube.com/watch?v=mizS4KnfTtQ
- A. Homescu “Mutating the clang AST from Plugins”: https://www.youtube.com/watch?v=_rUwW8Awc5s