Advanced Topics in Compilers

LLVM

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Outline

- Summary of 323: LLVM

- Summary of 323: LLVM IR

- Summary of 323: Dependences

LLVM

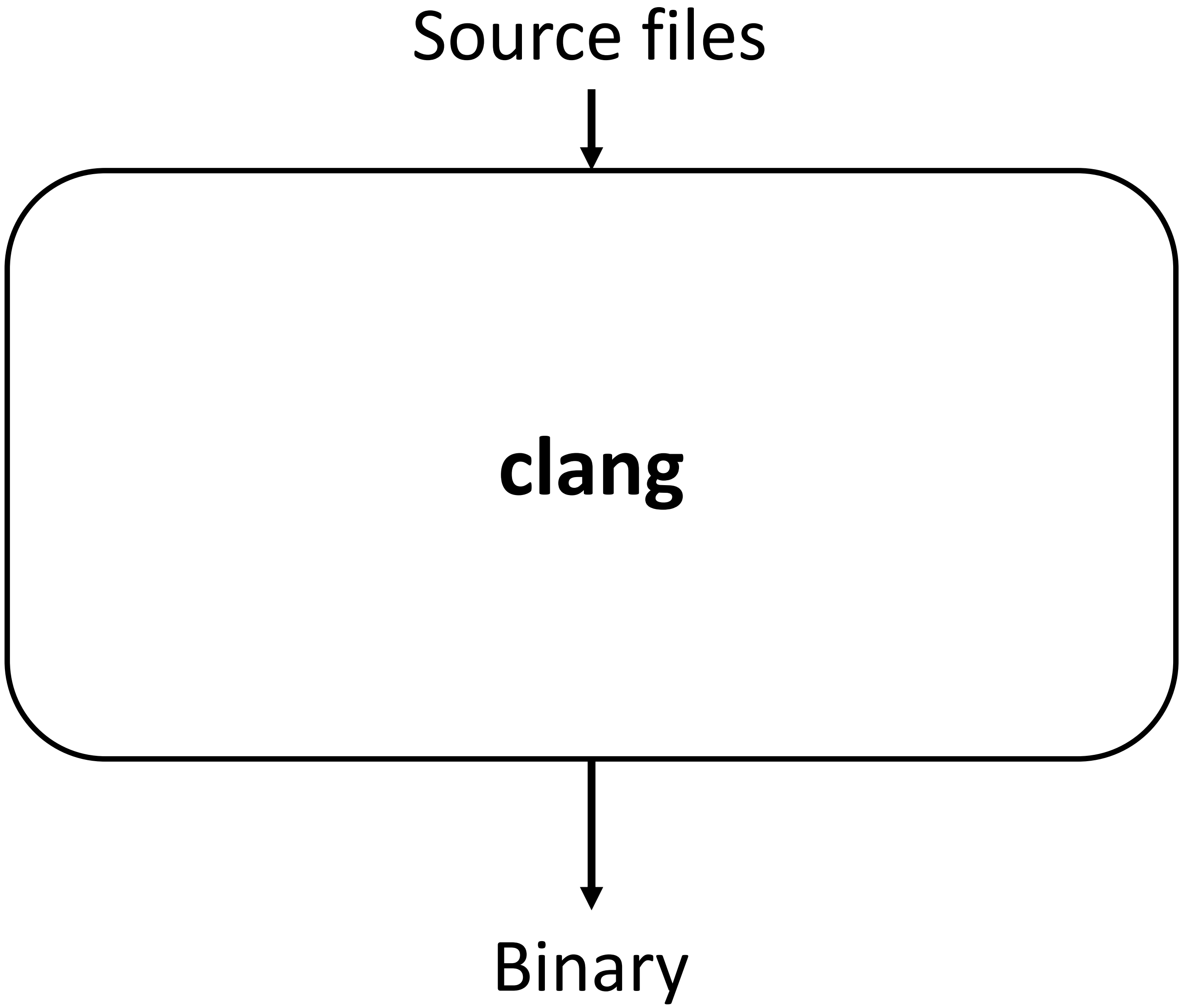
- LLVM is a great, hackable compiler for C/C++ languages
  - C, C++, Objective-C
- But it’s also
  - A dynamic compiler
  - A compiler for bytecode languages (e.g., Java, CIL bytecode)
- LLVM IR: bitcode
- LLVM is modular and well documented
- Started from UIUC, it’s now the research tool of choice
- It’s an industrial-strength compiler

  Apple, AMD, Intel, NVIDIA

LLVM tools

- clang: compile C/C++ code as well as OpenMP code
- clang-format: to format C/C++ code
- clang-tidy: to detect and fix bug-prone patterns, performance, portability and maintainability issues
- clangd: to make editors (e.g., vim) smart
- clang-rename: to refactor C/C++ code
- SAFECode: memory checker
- lldb: debugger
- lld: linker
- polly: parallelizing compiler
- libclc: OpenCL standard library
- dragonegg: integrate GCC parsers
- vmkit: bytecode virtual machines
- … and many more

LLVM common use at 10000 feet

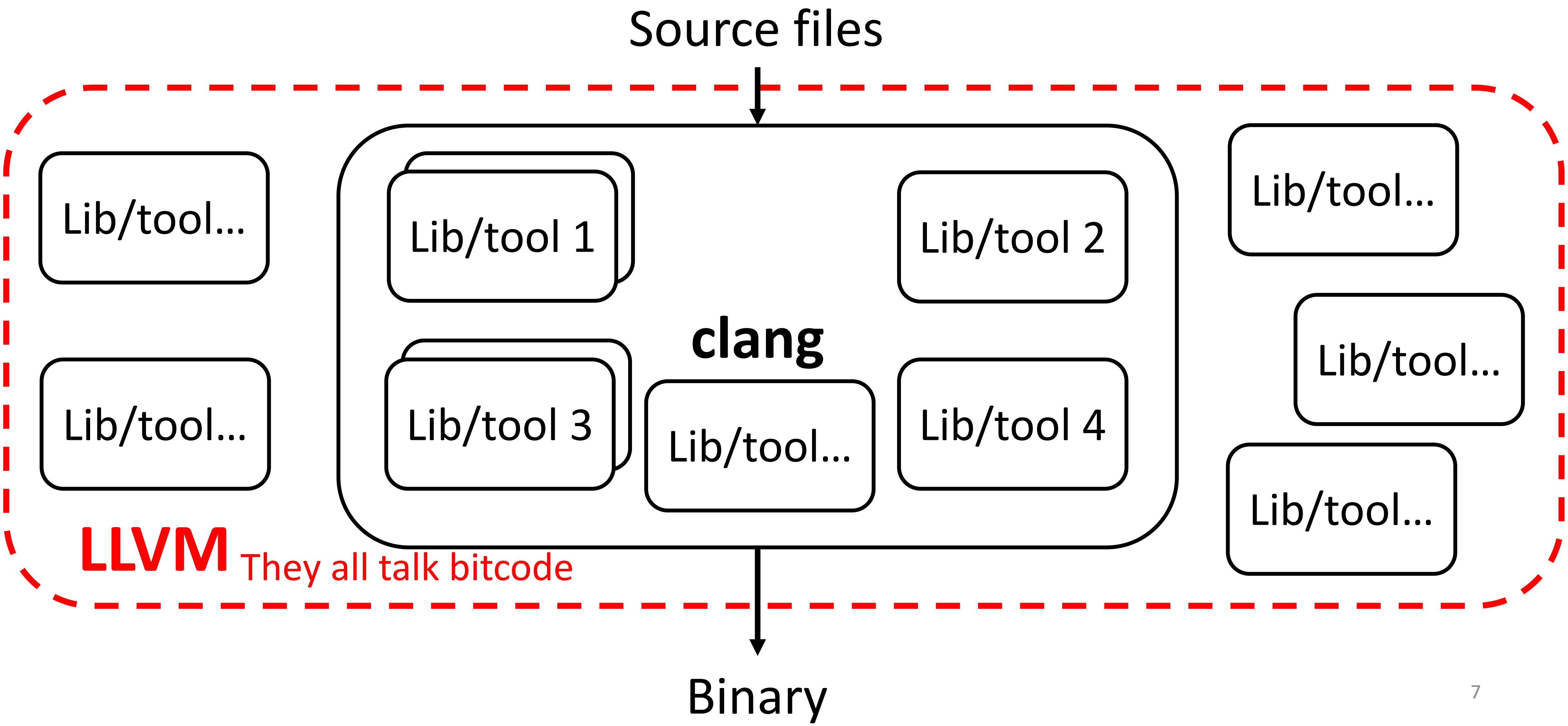


LLVM common use at 10000 feet

Source files

Binary

LLVM common use at 10000 feet



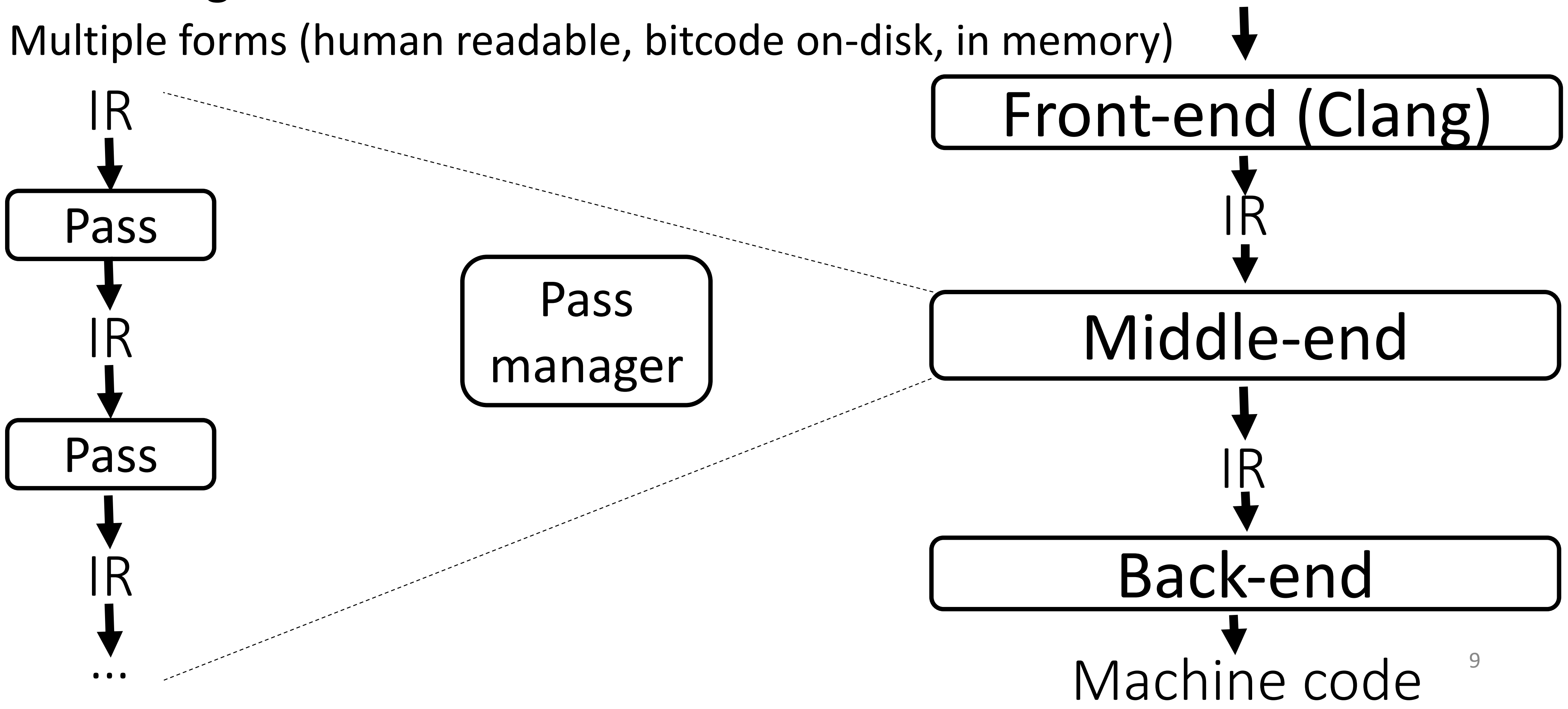
LLVM internals

- A component is composed of pipelines
  - Each stage: reads something as input and
    generates something as output
  - To develop a stage: specify how to transform the input
    to generate the output

- Some complexity lies in linking stages

LLVM and other compilers

- LLVM is designed around it's IR
  - Multiple forms (human readable, bitcode on-disk, in memory)



Pass manager

- The pass manager orchestrates passes

- It builds the pipeline of passes in the middle-end

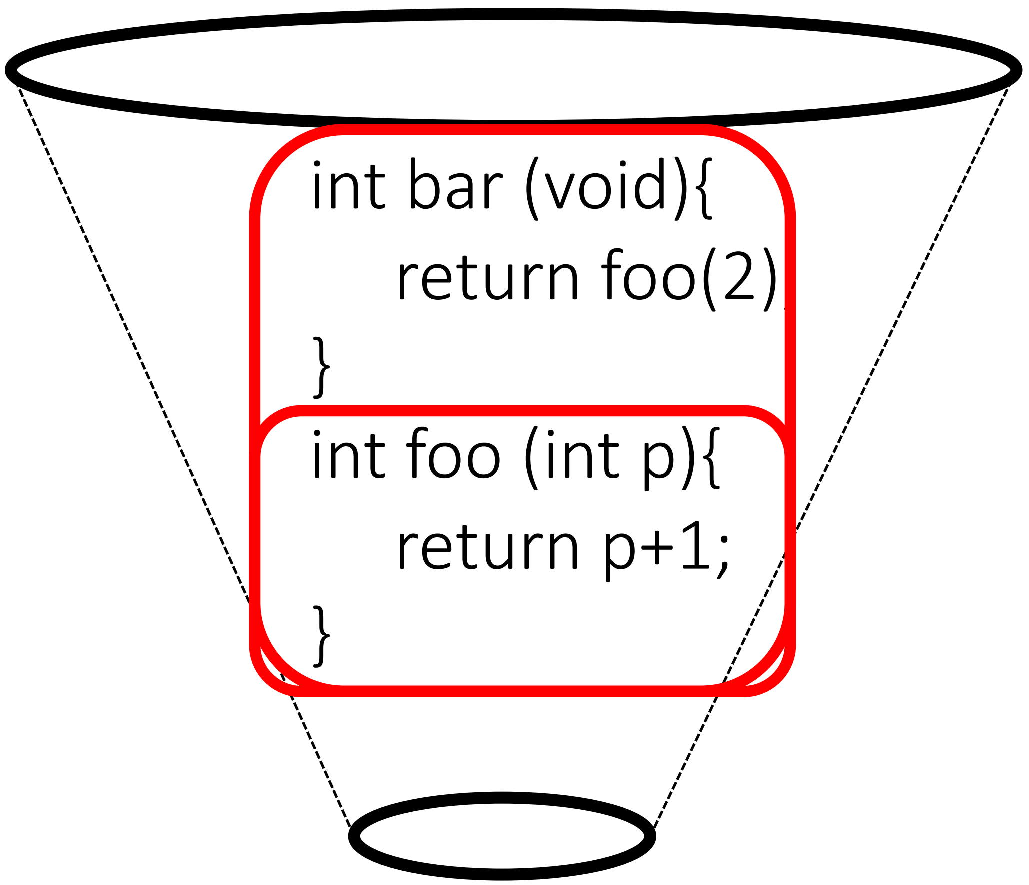
- The pipeline is created by respecting the dependences declared by each pass

  Pass X depends on Y
  Y will be invoked before X

Pass types

Use the “smallest” one for your project

- CallGraphSCCPass
- ModulePass
- FunctionPass
- LoopPass
- BasicBlockPass



Adding a pass

- Internally

clang | vmkit | …

- Externally
  - More convenient to develop (compile-debug loop is much faster!)

clang | vmkit | …

https://github.com/scampanoni/LLVM_middleend_template

CatPass.cpp

```cpp
#include "llvm/Pass.h"
#include "llvm/IR/Function.h"
#include "llvm/Support/raw_ostream.h"
#include "llvm/IR/LegacyPassManager.h"
#include "llvm/Transforms/IPO/PassManagerBuilder.h"

using namespace llvm;
```

```cpp
namespace {
  struct CAT : public FunctionPass {
    static char ID;

    CAT() : FunctionPass(ID) {}

    bool doInitialization (Module &M) override {
      errs() << "Hello LLVM World at \"doInitialization\"\n" ;
      return false;
    }

    bool runOnFuncti
      errs() << "Hel
      return false;
    }

    void getAnalysis
      errs() << "Hel
      AU.setPreserve
    }
  };
}
```

```cpp
// Next there is code to register your pass to "opt"
char CAT::ID = 0;
static RegisterPass<CAT> X("CAT", "Homework for the CAT class");

// Next there is code to register your pass to "clang"
static CAT * _PassMaker = NULL;
static RegisterStandardPasses _RegPass1(PassManagerBuilder::EP_OptimizerLast,
    [](const PassManagerBuilder&, legacy::PassManagerBase& PM) {
        if(!_PassMaker){ PM.add(_PassMaker = new CAT());}}); // ** for -Ox
static RegisterStandardPasses _RegPass2(PassManagerBuilder::EP_EnabledOnOptLevel0,
    [](const PassManagerBuilder&, legacy::PassManagerBase& PM) {
        if(!_PassMaker){ PM.add(_PassMaker = new CAT()); }}); // ** for -O0
```

Outline

- Summary of 323: LLVM

- Summary of 323: LLVM IR

- Summary of 323: Dependences

Passes

- A compilation pass reads and (sometime) modifies the bitcode (LLVM IR)

- If you want to understand code properties:
  you need to understand the bitcode

- If you want to modify the bitcode:
  you need to understand the bitcode first

LLVM IR (a.k.a. bitcode)

- RISC-based
  - Instructions operate on variables
  - Load and store to access memory

- Include high level instructions
  - Function calls (call, invoke)
  - Pointer arithmetics (getelementptr)

LLVM IR (2)

- Strongly typed
  - No assignments of variables with different types
  - You need to explicitly cast variables
  - Load and store to access memory

- Variables
  - Global (@myVar)
  - Local to a function (%myVar)
  - Function parameter (define i32 @myF (i32 %myPar))

LLVM IR (3)

- 3 different (but 100% equivalent) formats
  - Assembly: human-readable format (FILENAME.ll)
  - Bitcode: machine binary on-disk (FILENAME.bc)
  - In memory: in memory binary

- Generating IR
  - Clang for C-like languages (similar options w.r.t. GCC)
  - Different front-ends available

LLVM IR (4)

It’s a Static Single Assignment (SSA) representation

- A variable is set only by one instruction in the function body

  %myVar = ...

- A static assignment can be executed more than once

SSA and not SSA example

```
float myF (float par1, float par2, float par3){
    return (par1 * par2) + par3; }
```

```
define float @myF(float %par1, float %par2, float %par3) {
    %1 = fmul float %par1, %par2
    %1 = fadd float %1, %par3
    ret float %1 }
```

NOT SSA

```
define float @myF(float %par1, float %par2, float %par3) {
    %1 = fmul float %par1, %par2
    %2 = fadd float %1, %par3
    ret float %2 }
```

SSA

SSA and not SSA

- Passes applied to SSA-based code are faster!
  - Old compilers aren’t SSA-based
  - Transforming IR in its SSA-form takes time

- When designing your pass, think carefully about SSA
  - Take advantage of its properties

LLVM tools to read/generate IR

- clang to compile/optimize/generate LLVM IR code
  - To generate binaries from source code or IR code

- lli to execute (interpret/JIT) LLVM IR code

  lli FILE.bc

- llc to generate assembly from LLVM IR code

  llc FILE.bc

LLVM tools to read/generate IR

- opt to analyze/transform LLVM IR code
  - Read LLVM IR file
  - Load external passes
  - Run specified passes
  - Respect pass order you specify as input
    - opt -pass1 -pass2 FILE.ll
  - Optionally generate transformed IR
- Useful passes
  - opt -view-cfg FILE.ll
  - opt -view-dom FILE.ll
- opt -help

Running LLVM passes

opt –load MYPASS.so –CAT A.bc –o B.bc

```
// Next there is code to register your pass to "opt"
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    [](const PassManagerBuilder&, legacy::PassManagerBase& PM) {
        if(!_PassMaker){ PM.add(_PassMaker = new CAT()); }}); // ** for -O0
```

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- Summary of 323: Dependences

Dependences: the big picture

- Code transformations are designed
  to preserve the “semantics” of the code given as input
  - What is the “semantics” of a program?

```
1: varX = par1 + 1
2: varY = par2 + par1
3: varZ = varY + varX
4: print(varZ)
```

```
4: print(varZ)
1: varX = par1 + 1
2: varY = par2 + par1
3: varZ = varX + varY
```

```
2: varY = par2 + par1
1: varX = par1 + 1
3: varZ = varX + varY
4: print(varZ)
```

- A dependence A -> B is satisfied if
  A will always execute before B
- If we satisfy all dependences in the code,
  then we will preserve I => O

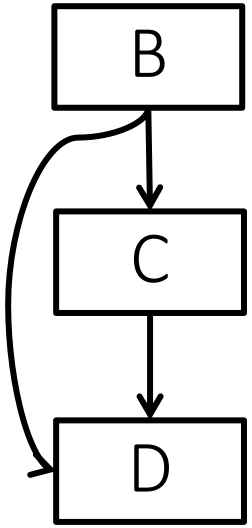
```
A: varX = 1;
B: if (par1 > 5)
C:     varX = par1 + 1
D: print(varX)
```

Control dependence intuition

- Dependence: C will be executed depending on B

- How to identify C? (automatically)
  - We need a Control Flow Analysis

```
A: varX = 1;
B: if (par1 > 5)
C:     varX = par1 + 1
D: print(varX)
```

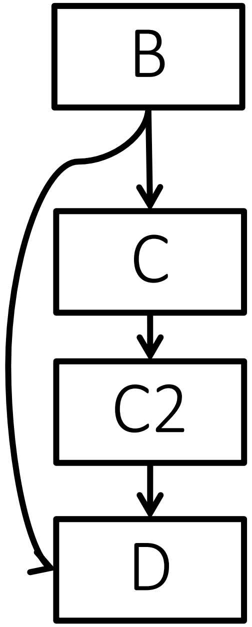


CFG

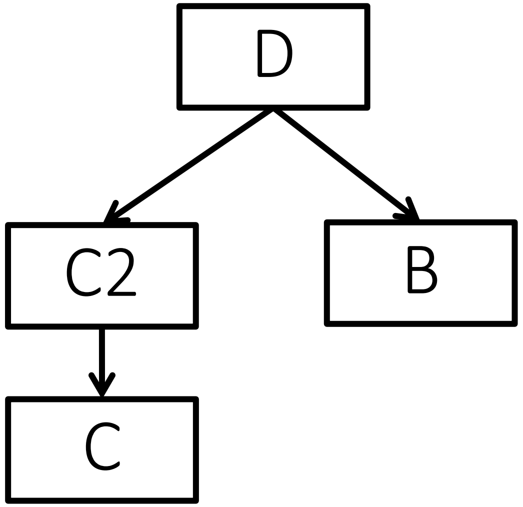
Post-dominators

Assumption: Single exit node in CFG

Definition: Node *d* post-dominates node *n* in a graph
if every path from *n* to the exit node goes through *d*



CFG



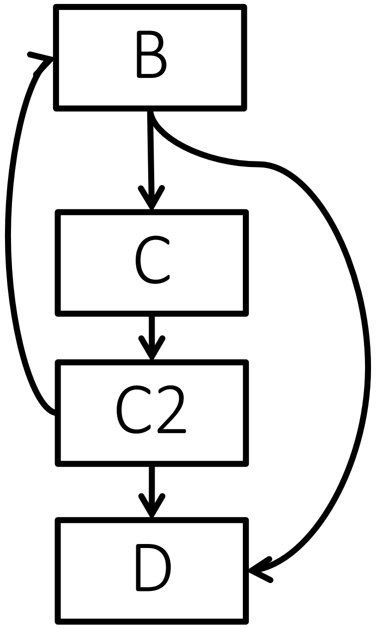
Immediate
post-dominator tree

```
B: if (par1 > 5)
C:     varX = par1 + 1
C2:   …
D: print(varX)
```

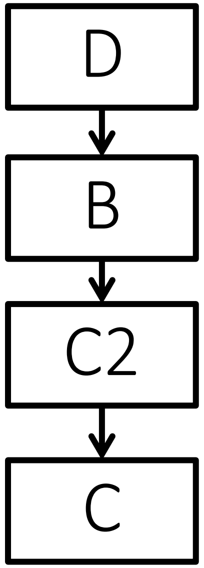
Control dependences

A node *Y* control-depends on another node *Y* if and only if

1. There is a path from X to Y such that
   every node in that path other than X and Y is post-dominated by Y
2. X is not strictly post-dominated by Y



CFG



Immediate
post-dominator tree

```
B: while (par1 > 5)
C:     varX = par1 + 1
C2:   ...
D: print(varX)
```

Data dependences

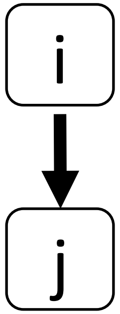
- Gives constraints on parallelism that must be satisfied

- Must be satisfied to have correct program
  - How can we satisfy data dependences?

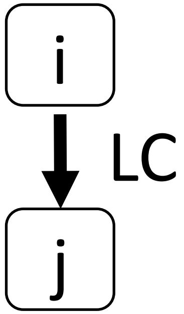
- Any order that does not violate these dependences is correct!

Loop-carried data dependences

```
while(…){
  i: x = …;
  j: *p = x + 1;
  …
}
```




```
while(…){
  j: *p = x + 1;
  i: x = …;
  …
}
```



Loop-carried data dependences

```
while(…){
   j: *p = x + 1;
   i: x = …;
   …
}
```


```
while(…){
   j: *p = A[i-2] + 1;
   i: A[i] = …;
   k: i++;
}
```

Program dependence graph (PDG)

- Program Dependence Graph = Control Dependence Graph +
  Data Dependences

- Facilitates performing most traditional optimizations
  - Constant folding, scalar propagation, common subexpression elimination, code motion, strength reduction, code parallelization, code vectorization, etc…

- Requires only single walk over PDG

Strongly Connected Component (SCC)

Often you need to partition instructions in groups

- Where each group is composed of instructions that depend on each other

Core 0

```
i0: while (i <= N)
i1:     X = Y + 1
i2:     K = Z * 5
i3:     Y = X * 42
i4:     Z = K + 2
i5:     i = i + 1
```

Core 0

```
i1:     X = Y + 1
i3:     Y = X * 42
```

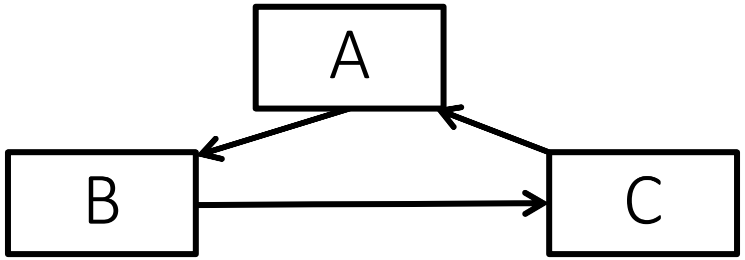
Core 1

```
i2:     K = Z * 5
i4:     Z = K + 2
```

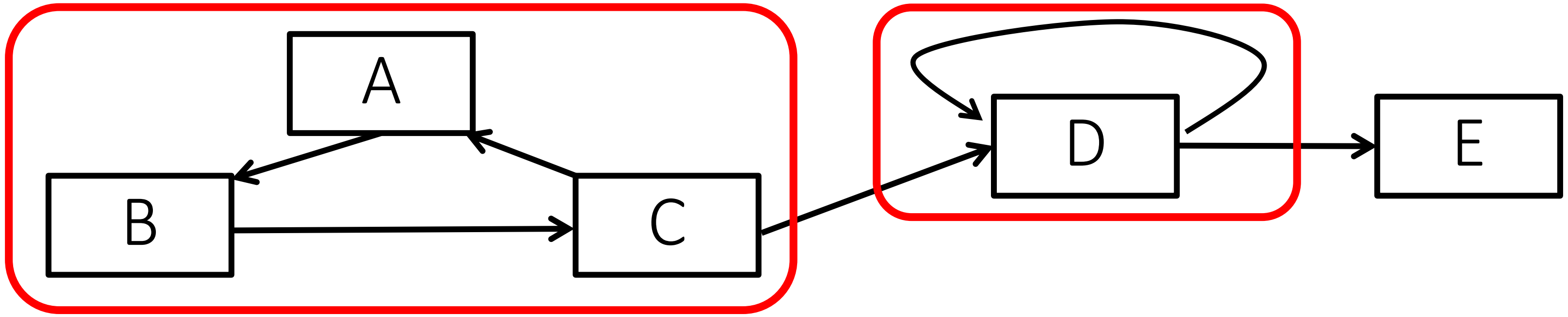
Different colors <-> different cycles in the PDG => different cores

Strongly Connected Component (SCC)

- A directed graph is strongly connected if there is a path between all pairs of vertices



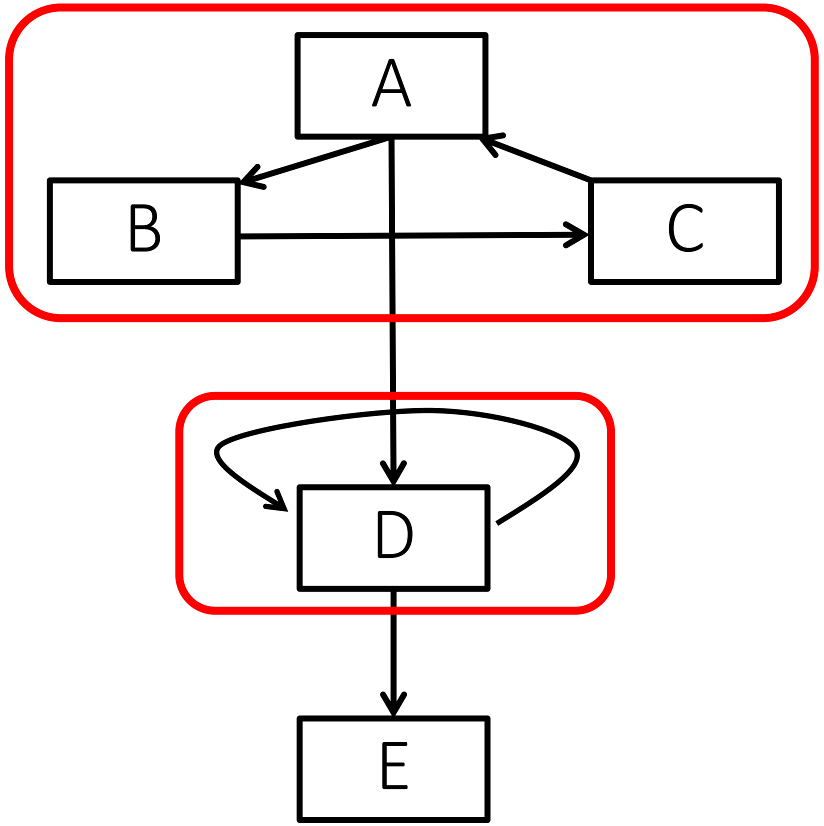
- A strongly connected component (**SCC**) of a directed graph is a maximal strongly connected subgraph



SCCDAG

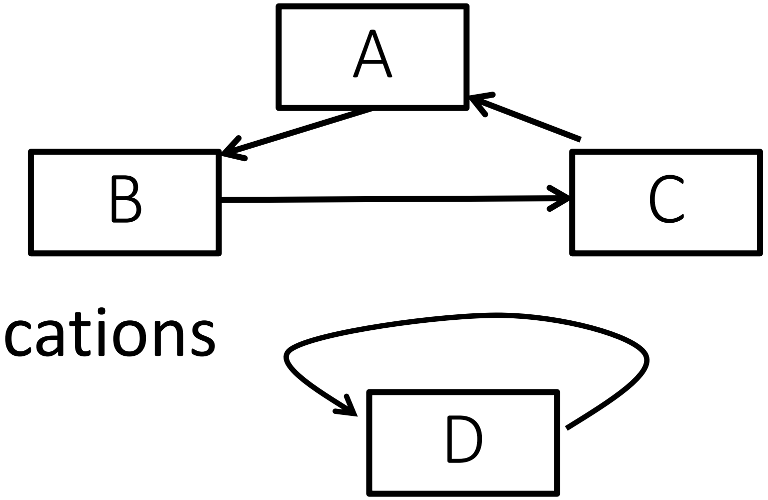
- From the PDG

- To the SCC identifications

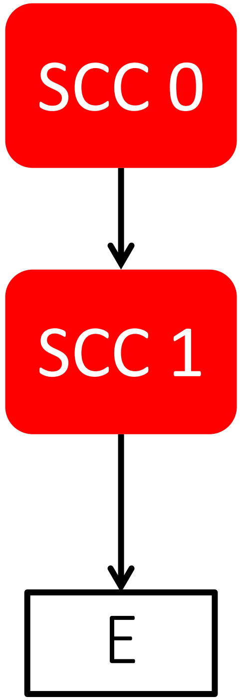


SCCDAG

- From the PDG
- To the SCC identifications
- To the SCCDAG




```
i0: while (i <= N)
i1:     X = Y + 1
i2:     K = Z * 5
i3:     Y = X * 42
i4:     Z = K + 2
i5:     i = i + 1
```



Always have faith in your ability

Success will come your way eventually

Best of luck!