Advanced Topics *in* Compilers

Call Graph

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Outline

- Call graph (summary from 323)

- Call graph in NOELLE

- Other abstractions generated from call graph in NOELLE

Call graph

- First problem: how do we know what procedures are called from where?
    - Especially difficult in higher-order languages, languages where functions are values
    - What about C programs?
    - We’ll ignore this for now

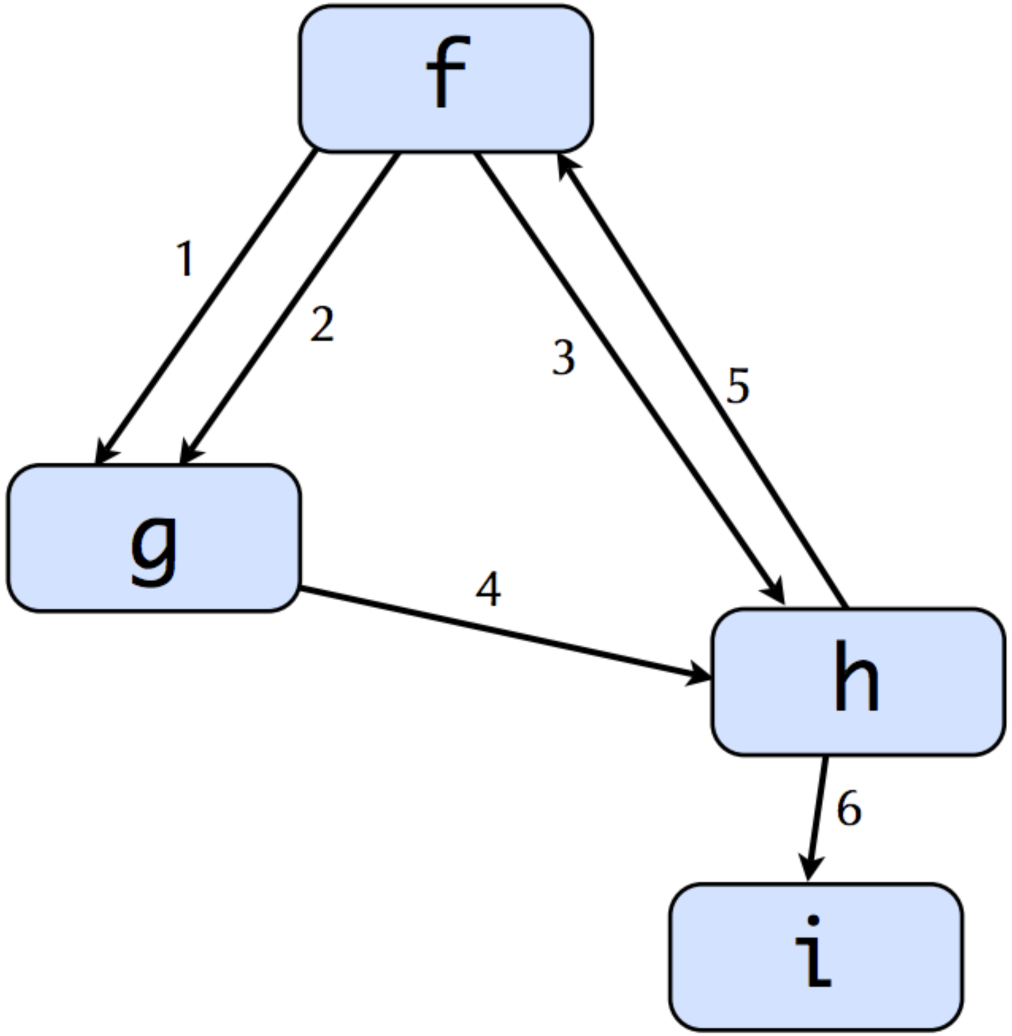
```
void foo (int a, int (*p_to_f)(int v)){
  int l = (*p_to_f)(5);
  a = l + 1;
  return a;
}
```

- Let’s assume we have a (static) **call graph**
    - Indicates which procedures can call which other procedures, and from which program points

Call graph example

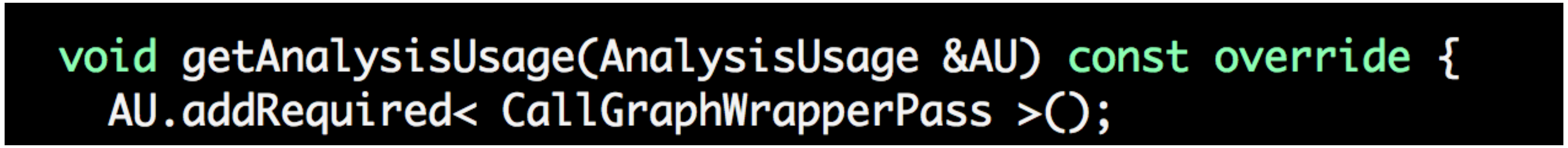
```
f() {
   1:  g();
   2:  g();
   3:  h();
}

g() {
   4: h();
}

h() {
   5: f();
   6: i();
}

i() { … }
```

From now on we assume we have a static call graph



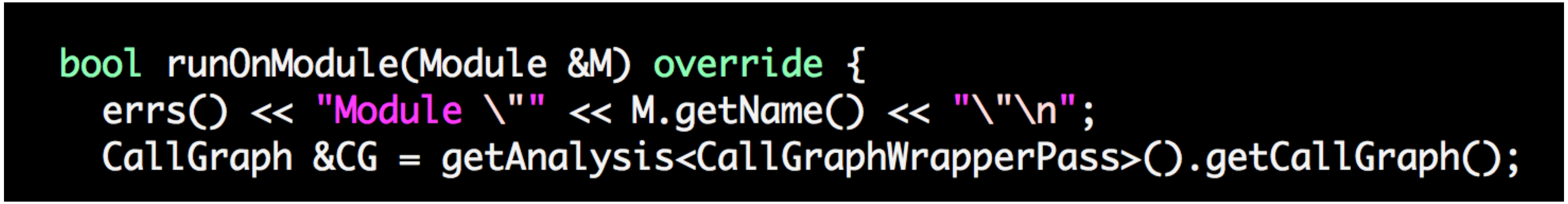
Using CallGraphWrappingPass

- Declaring your pass dependence



```
void getAnalysisUsage(AnalysisUsage &AU) const override {
  AU.addRequired< CallGraphWrapperPass >();
```

- Fetching the call graph



```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";
  CallGraph &CG = getAnalysis<CallGraphWrapperPass>().getCallGraph();
```

Call graph

- how do we know
  what procedures are called from where?
  - Especially difficult in higher-order languages, languages where functions are values
  - What about C programs?

```
void foo (int a, int (*p_to_f)(int v)){
  int l = (*p_to_f)(5);
  a = l + 1;
  return a;
}
```

- Call graph generated by LLVM:
  - If the callee is unknown: no edge is generated
  - If there are N possible callees (N > 1): no edge is generated
  - In other words: the call graph of LLVM **is not** complete

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Call graph in NOELLE

- Called “Program Call Graph (PCG)”
- PCG is complete (and conservative)
- If there are N possible callees (N > 1): there are N outgoing edges
- It is a hierarchical graph

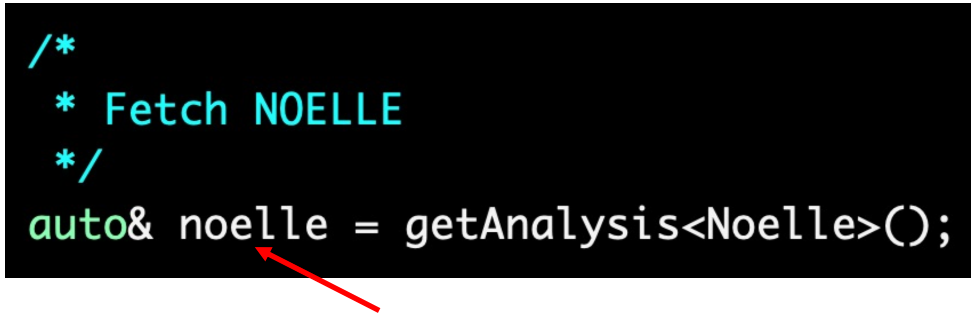
Let’s compute the PCG

Normalize the code

Code must be normalized before you use NOELLE

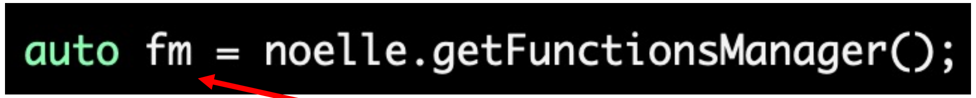
- noelle-norm MYIR.bc –o IR.bc
  or
- noelle-simplification MYIR.bc –o IR.bc

Fetching the program call graph (PCG)



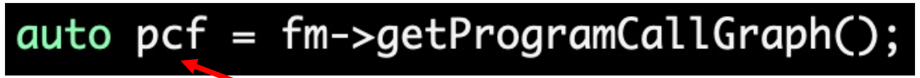
```
/*
 * Fetch NOELLE
 */
auto& noelle = getAnalysis<Noelle>();
```

llvm::noelle::Noelle



```
auto fm = noelle.getFunctionsManager();
```

llvm::noelle::FunctionsManager *

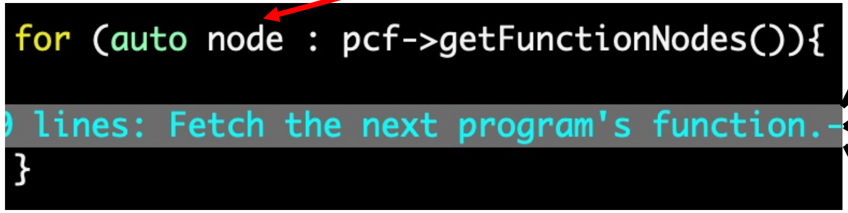


```
auto pcf = fm->getProgramCallGraph();
```

llvm::noelle::CallGraph *

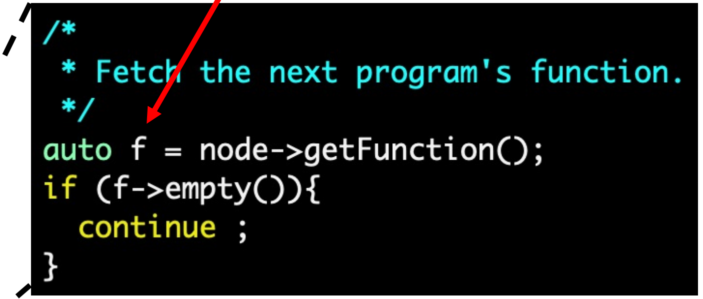
Using the PCG

llvm::noelle::CallGraphFunctionNode *

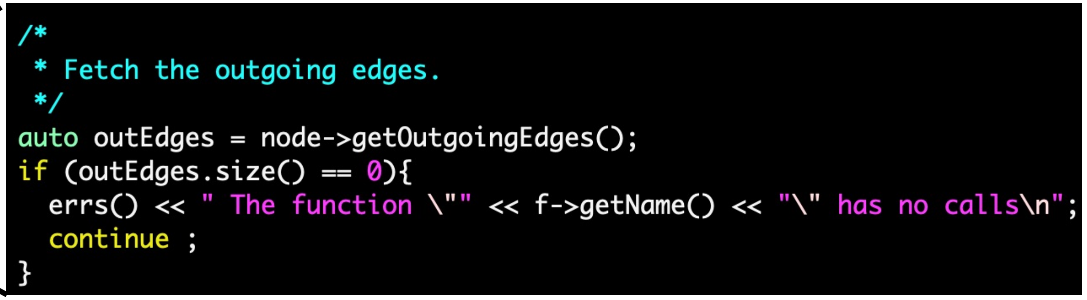


```
for (auto node : pcf->getFunctionNodes()){
) lines: Fetch the next program's function.-
}
```

llvm::Function *



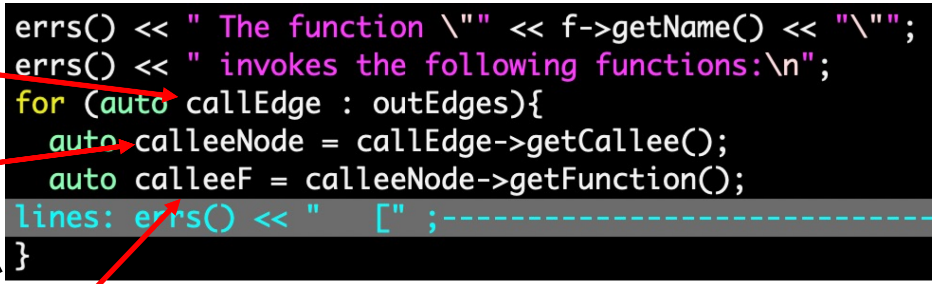
```
/*
 * Fetch the next program's function.
 */
auto f = node->getFunction();
if (f->empty()){
  continue ;
}
```



```
/*
 * Fetch the outgoing edges.
 */
auto outEdges = node->getOutgoingEdges();
if (outEdges.size() == 0){
  errs() << " The function \"" << f->getName() << "\" has no calls\n";
  continue ;
}
```

llvm::noelle::CallGraphFunctionFunctionEdge *

llvm::noelle::CallGraphFunctionNode *

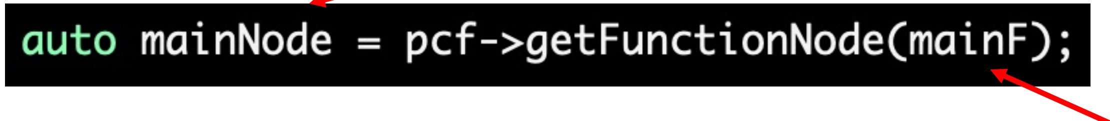


```
errs() << " The function \"" << f->getName() << "\"";
errs() << " invokes the following functions:\n";
for (auto callEdge : outEdges){
  auto calleeNode = callEdge->getCallee();
  auto calleeF = calleeNode->getFunction();
lines: errs() << "    [" ;-----------------------------
}
```

llvm::Function *

PCG: from function to node

llvm::noelle::CallGraphFunctionNode *



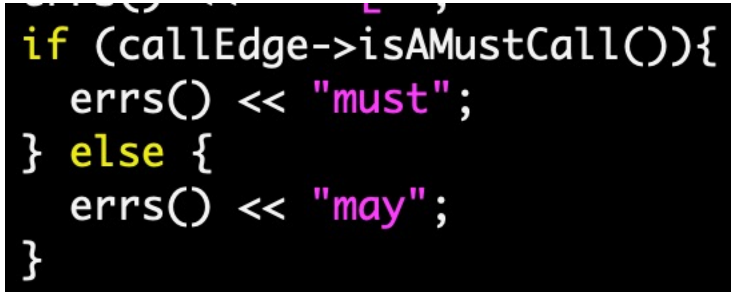
```
auto mainNode = pcf->getFunctionNode(mainF);
```

llvm::Function *

Edges in the PCG

LLVM call graph edges

- Two type of edges: may and must
  - May:
    when the related call executes,
    the destination of the edge might be called
  - Must:
    when the related call executes,
    the destination of the edge will always execute



```
if (callEdge->isAMustCall()){
  errs() << "must";
} else {
  errs() << "may";
}
```

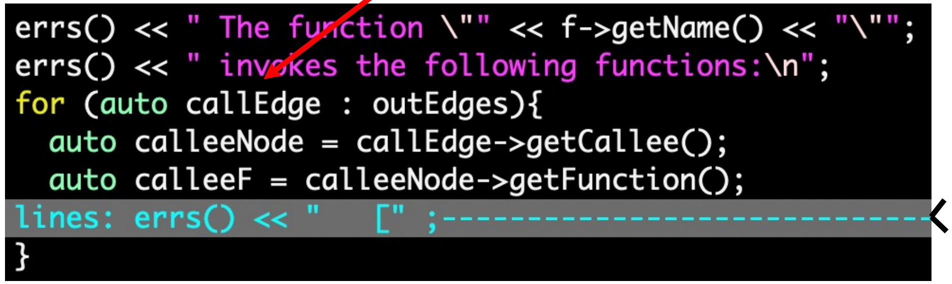
PCG of NOELLE is hierarchical

- If a function F invokes G N times,
  the PCG includes only one edge e from F to G
  - Source of e: F
  - Destination of e: G

- That edge includes N sub-edges
  - Source of a sub-edge: the specific **call instruction** of F
  - Destination of all sub-edges: **function** G

PCG of NOELLE is hierarchical

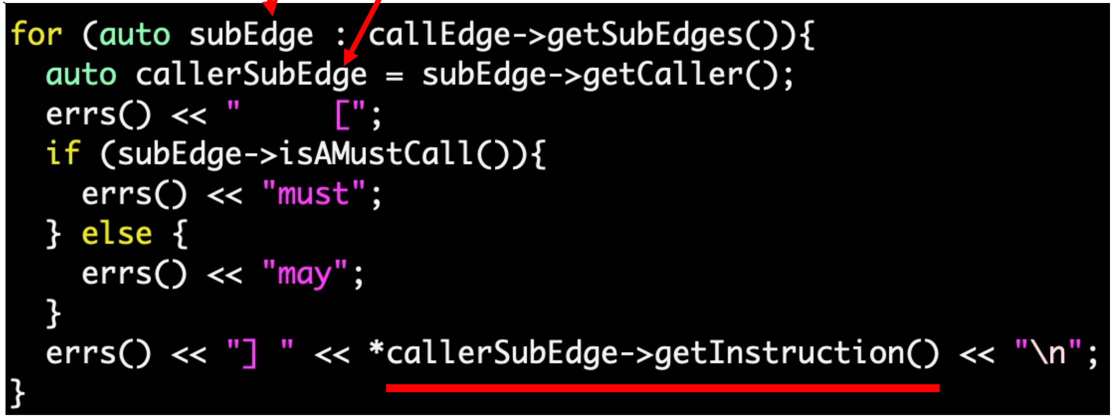
llvm::noelle::CallGraphFunctionFunctionEdge *



```
errs() << " The function \"" << f->getName() << "\"";
errs() << " invokes the following functions:\n";
for (auto callEdge : outEdges){
  auto calleeNode = callEdge->getCallee();
  auto calleeF = calleeNode->getFunction();
lines: errs() << "   [" ;------------------------------
}
```

llvm::noelle::CallGraphInstructionFunctionEdge *

llvm::noelle::CallGraphInstructionNode *



```
for (auto subEdge : callEdge->getSubEdges()){
  auto callerSubEdge = subEdge->getCaller();
  errs() << "      [";
  if (subEdge->isAMustCall()){
    errs() << "must";
  } else {
    errs() << "may";
  }
  errs() << "] " << *callerSubEdge->getInstruction() << "\n";
}
```

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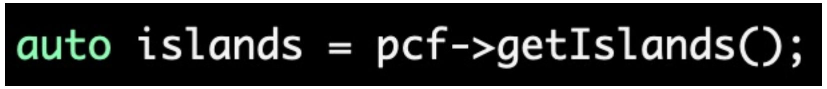
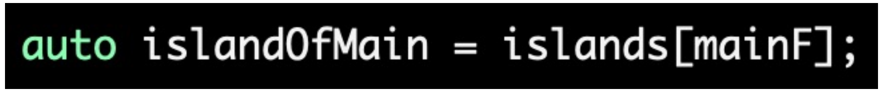
Islands

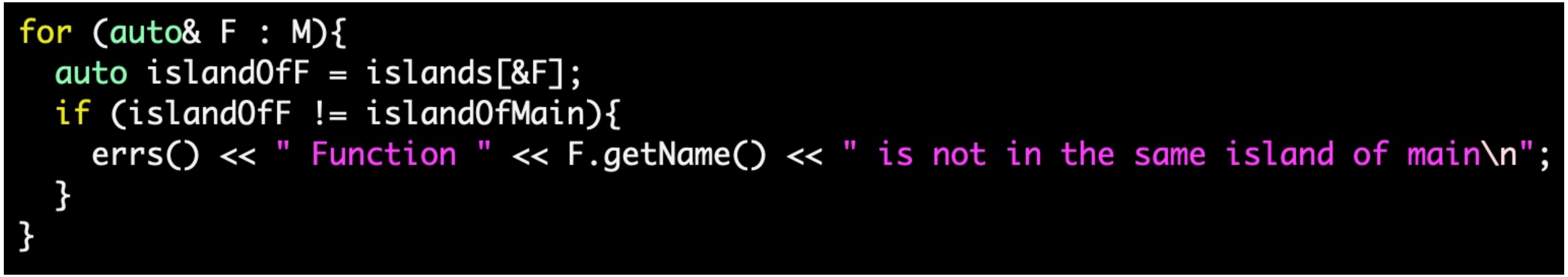
- Island: disconnected sub-graph of a graph
- Island in the PCG:
  set of functions that **cannot** reach
  from any other function of another island



```
auto islands = pcf->getIslands();
```

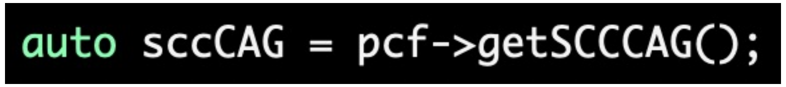


```
auto islandOfMain = islands[mainF];
```

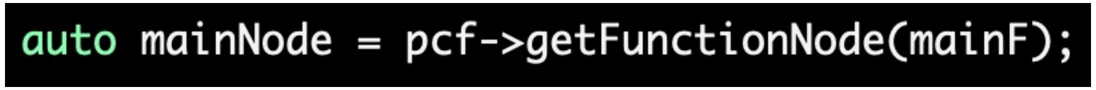


```
for (auto& F : M){
  auto islandOfF = islands[&F];
  if (islandOfF != islandOfMain){
    errs() << " Function " << F.getName() << " is not in the same island of main\n";
  }
}
```

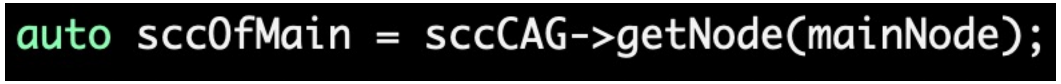
Strongly Connected Component Call Acyclic Graph (SCCCAG)



```
auto sccCAG = pcf->getSCCCAG();
```



```
auto mainNode = pcf->getFunctionNode(mainF);
```



```
auto sccOfMain = sccCAG->getNode(mainNode);
```

Always have faith in your ability

Success will come your way eventually

Best of luck!