Advanced Topics in Compilers

Dependences

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ὁ λόγος πλήρης χάριτος καὶ ἀλη-θείας
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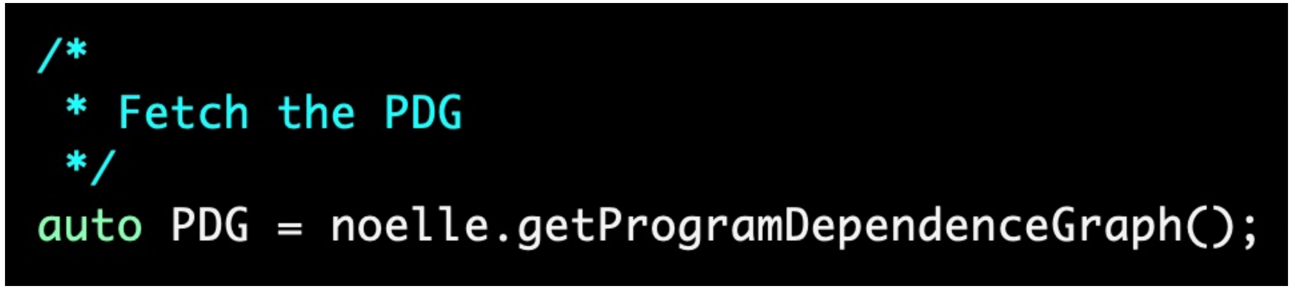
Outline

- Program Dependence Graph at the instruction granularity

- SCCDAG

- Semantics of dependences

PDG* is provided by NOELLE



```
/*
 * Fetch the PDG
 */
auto PDG = noelle.getProgramDependenceGraph();
```

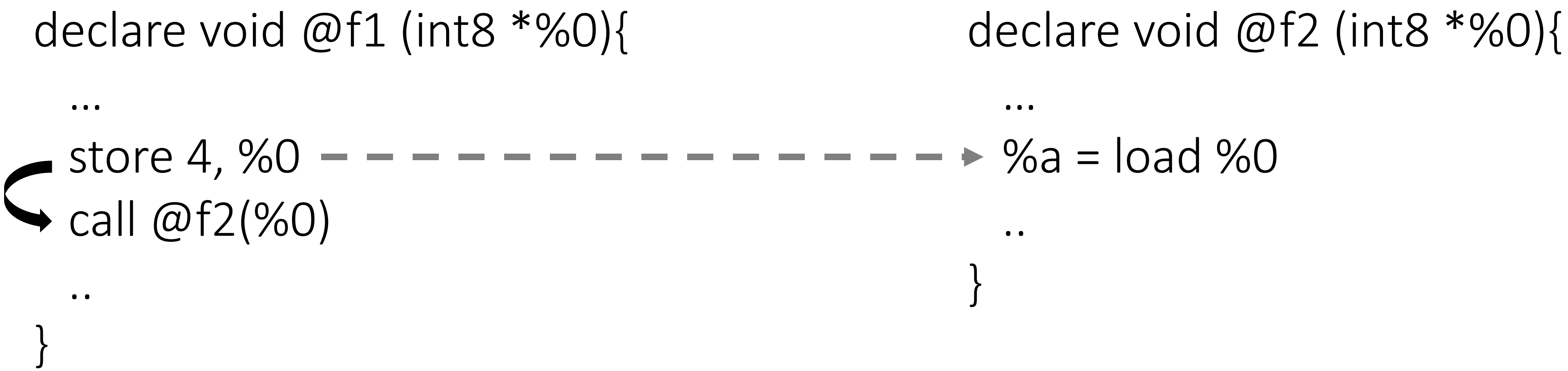
This PDG is at the instruction granularity

- A dependence is either
  - Between two instructions or
  - Between an instruction and a function parameter

[*] Jeanne Ferrante, Karl J. Ottenstein, Joe D. Warren.
The program dependence graph and its use in optimization. ACM Transactions on Programming Languages and System 1987

NOELLE’s PDG at the instruction granularity

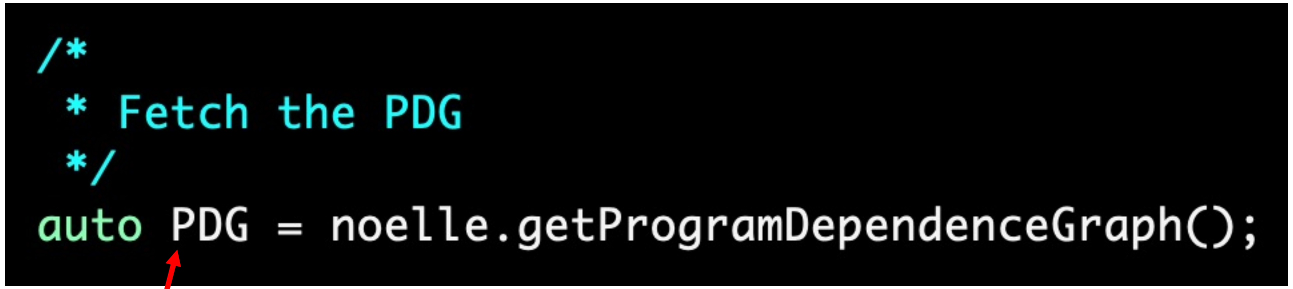
- Dependences are clustered by function
- Dependences between instructions in two functions:



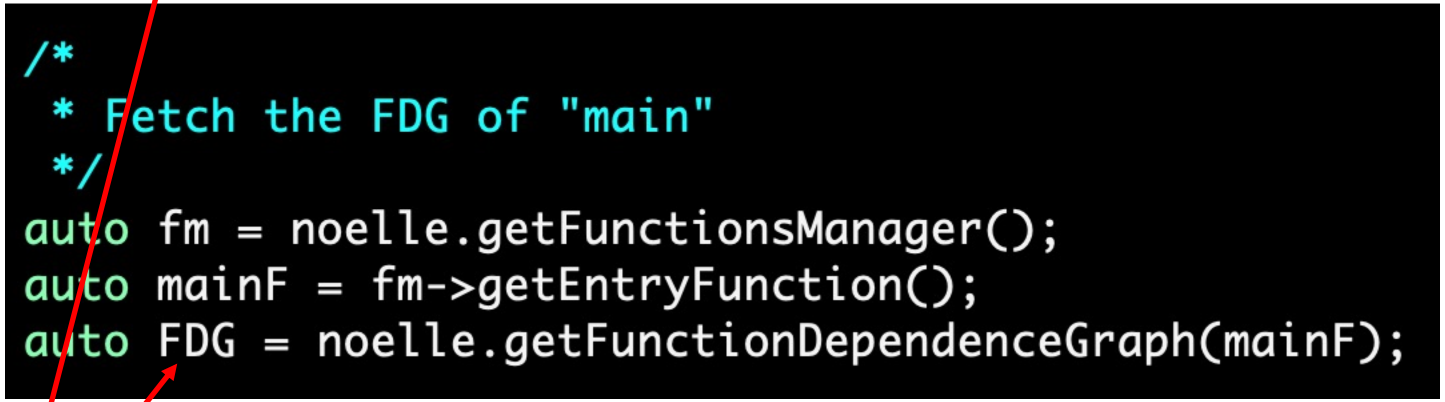
```
declare void @f1 (int8 *%0){
  …
  store 4, %0
  call @f2(%0)
  ..
}
```

```
declare void @f2 (int8 *%0){
  …
  %a = load %0
  ..
}
```

NOELLE’s Function Dependence Graph (FDG)



```
/*
 * Fetch the PDG
 */
auto PDG = noelle.getProgramDependenceGraph();
```



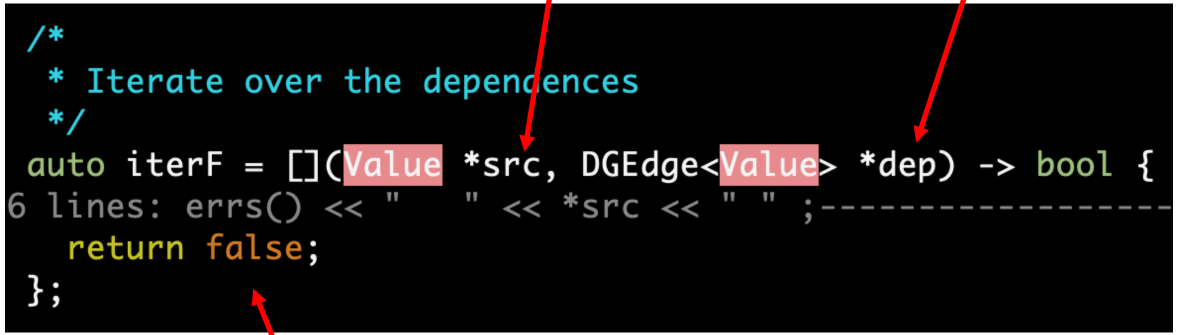
```
/*
 * Fetch the FDG of "main"
 */
auto fm = noelle.getFunctionsManager();
auto mainF = fm->getEntryFunction();
auto FDG = noelle.getFunctionDependenceGraph(mainF);
```

Different instances of the **same** C++ class (PDG)

PDG: iterating over dependences

Source of the current dependence edge

Current dependence



```
/*
 * Iterate over the dependences
 */
auto iterF = [](Value *src, DGEdge<Value> *dep) -> bool {
6 lines: errs() << "    " << *src << " " ;------------------
  return false;
};
```

Do you want to stop iterating?

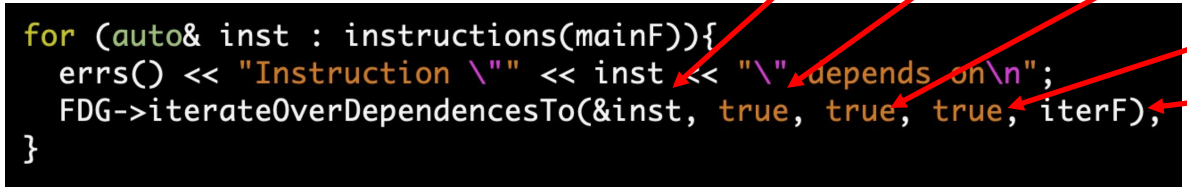
Iterating over incoming edges

Include control dependences

Include memory dependences

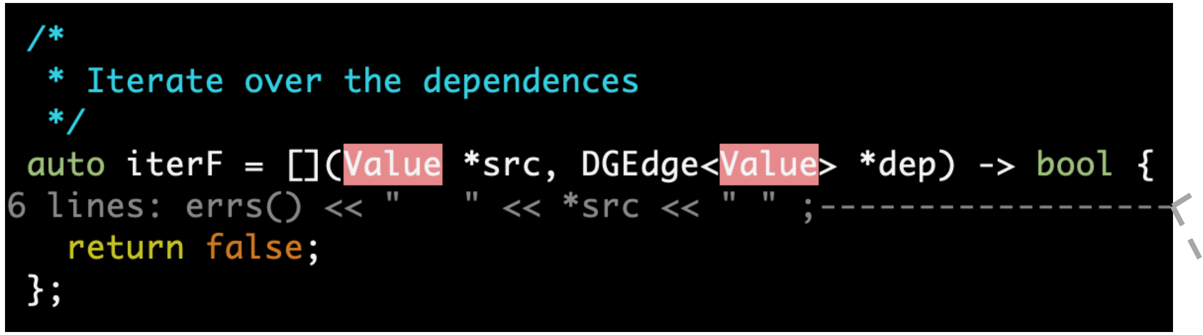
Include variable dependences

Function to invoke per edge

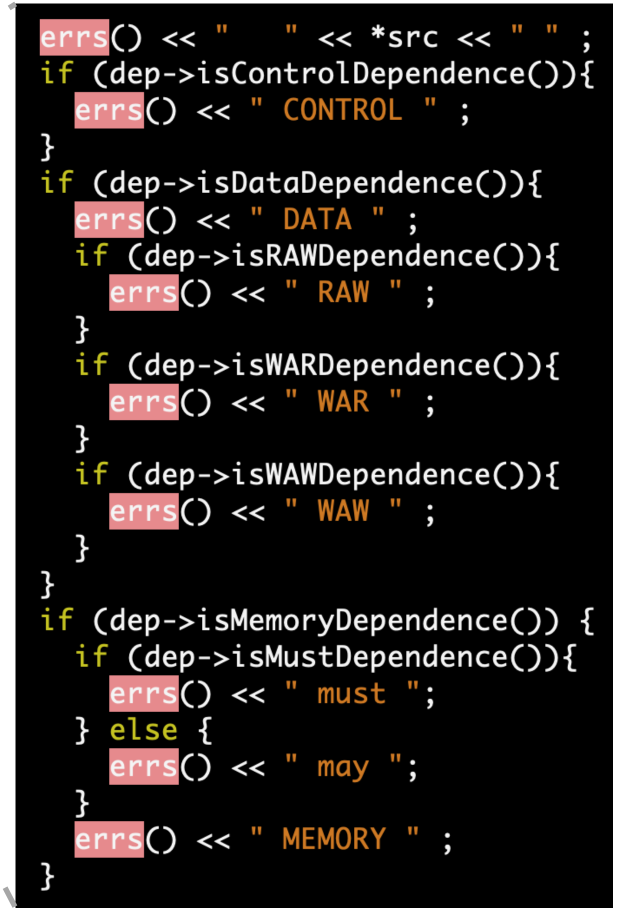


```
for (auto& inst : instructions(mainF)){
  errs() << "Instruction \"" << inst << "\" depends on\n";
  FDG->iterateOverDependencesTo(&inst, true, true, true, iterF);
}
```

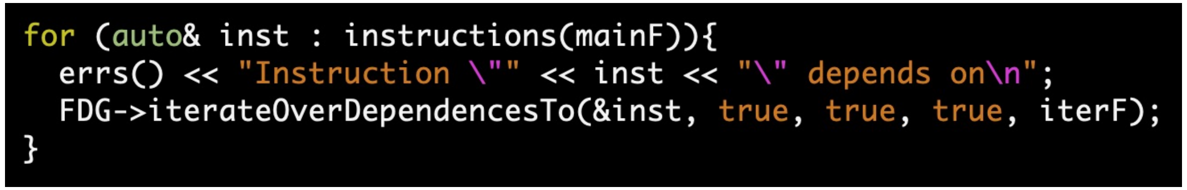
PDG: iterating over dependences



```
/*
 * Iterate over the dependences
 */
auto iterF = [](Value *src, DGEdge<Value> *dep) -> bool {
6 lines: errs() << "    " << *src << " " ;-----------------
  return false;
};
```

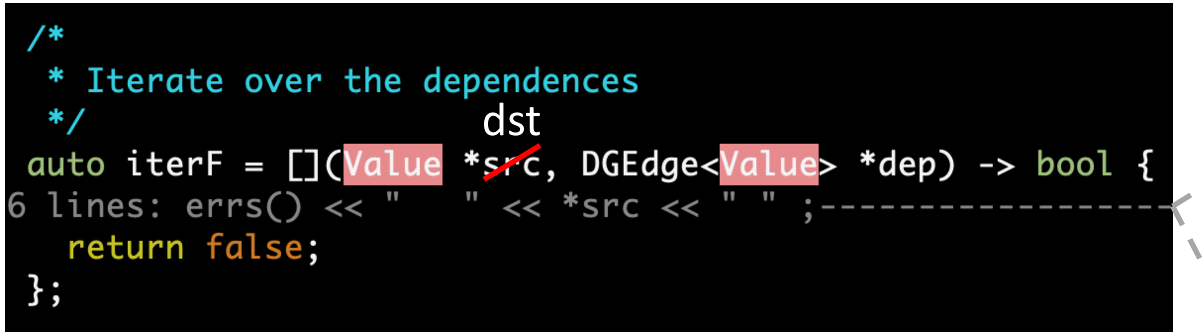


```
errs() << "    " << *src << " " ;
if (dep->isControlDependence()){
  errs() << " CONTROL " ;
}
if (dep->isDataDependence()){
  errs() << " DATA " ;
  if (dep->isRAWDependence()){
    errs() << " RAW " ;
  }
  if (dep->isWARDependence()){
    errs() << " WAR " ;
  }
  if (dep->isWAWDependence()){
    errs() << " WAW " ;
  }
}
if (dep->isMemoryDependence()) {
  if (dep->isMustDependence()){
    errs() << " must ";
  } else {
    errs() << " may ";
  }
  errs() << " MEMORY " ;
}
```

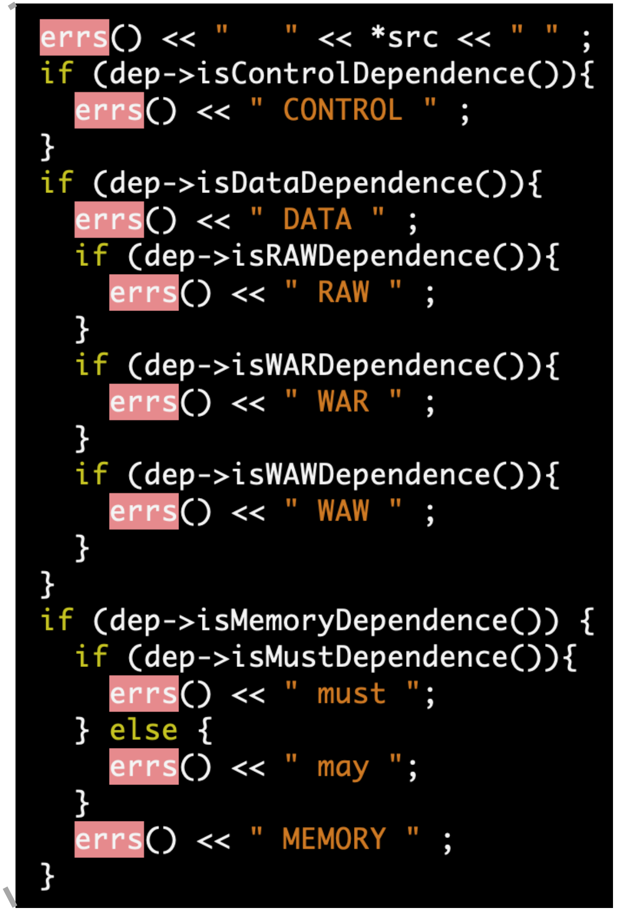


```
for (auto& inst : instructions(mainF)){
  errs() << "Instruction \"" << inst << "\" depends on\n";
  FDG->iterateOverDependencesTo(&inst, true, true, true, iterF);
}
```

PDG: iterating over dependences

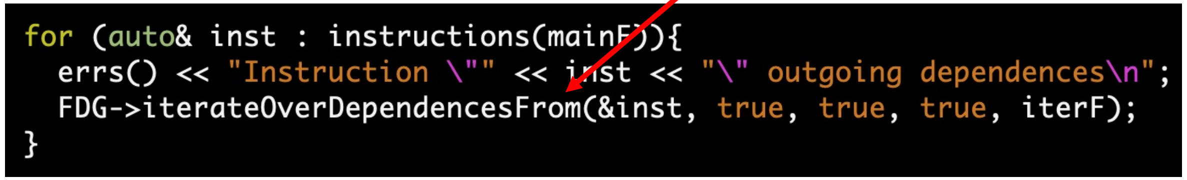


```
/*
 * Iterate over the dependences
 */                     dst
auto iterF = [](Value *~~src~~, DGEdge<Value> *dep) -> bool {
6 lines: errs() << "    " << *src << " " ;------------------
  return false;
};
```



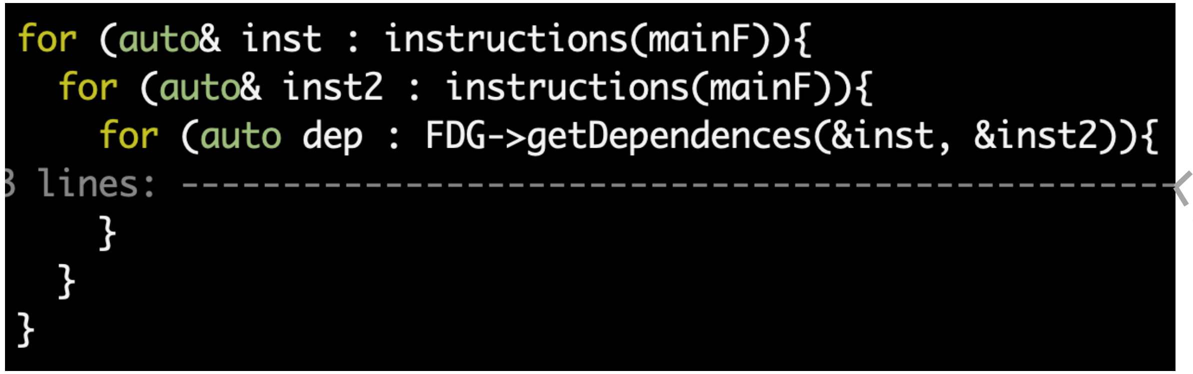
```
errs() << "    " << *src << " " ;
if (dep->isControlDependence()){
  errs() << " CONTROL " ;
}
if (dep->isDataDependence()){
  errs() << " DATA " ;
  if (dep->isRAWDependence()){
    errs() << " RAW " ;
  }
  if (dep->isWARDependence()){
    errs() << " WAR " ;
  }
  if (dep->isWAWDependence()){
    errs() << " WAW " ;
  }
}
if (dep->isMemoryDependence()) {
  if (dep->isMustDependence()){
    errs() << " must ";
  } else {
    errs() << " may ";
  }
  errs() << " MEMORY " ;
}
```

Iterating over outgoing edges

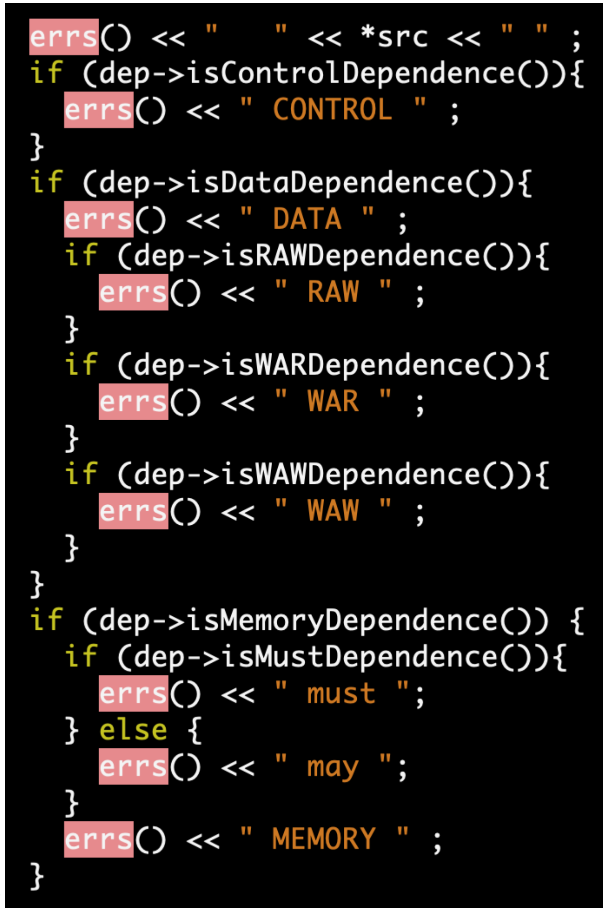


```
for (auto& inst : instructions(mainF)){
  errs() << "Instruction \"" << inst << "\" outgoing dependences\n";
  FDG->iterateOverDependencesFrom(&inst, true, true, true, iterF);
}
```

PDG: iterating over dependences



```
for (auto& inst : instructions(mainF)){
  for (auto& inst2 : instructions(mainF)){
    for (auto dep : FDG->getDependences(&inst, &inst2)){
3 lines: -----------------------------------------
    }
  }
}
```



```
errs() << "    " << *src << " " ;
if (dep->isControlDependence()){
  errs() << " CONTROL " ;
}
if (dep->isDataDependence()){
  errs() << " DATA " ;
  if (dep->isRAWDependence()){
    errs() << " RAW " ;
  }
  if (dep->isWARDependence()){
    errs() << " WAR " ;
  }
  if (dep->isWAWDependence()){
    errs() << " WAW " ;
  }
}
if (dep->isMemoryDependence()) {
  if (dep->isMustDependence()){
    errs() << " must ";
  } else {
    errs() << " may ";
  }
  errs() << " MEMORY " ;
}
```

NOELLE provides SCCDAG

- NOELLE provides:
  - Program Dependence Graph (PDG)
  - Function Dependence Graph (FDG)
  - Loop Dependence Graph (LDG) (see NOELLE_loops slides/talk)
- All dependence graphs are instances of the same class llvm::noelle::PDG
- Because of importance of loops, NOELLE provides a rich class for them called llvm::noelle::LoopDependenceInfo
- LoopDependenceInfo includes:
  - LDG
  - SCCDAG
  - And much more (see NOELLE_loops slides/talk)

Memory alias analysis: the problem (from 323)

- We want to
  - Execute *j* in parallel with *i* (extracting parallelism)
  - Move *j* before *i* (code scheduling)
- Does *j* depend on *i* ?

```
i: (*p) = varA + 1

j: varB = (*q) * 2
```

```
i: obj1.f = varA + 1

j: varB= obj2.f * 2
```

- Do p and q point to the same memory location?
  - Does q alias p?

Memory alias analyses included in NOELLE

- NOELLE relies on ~40 memory alias analyses to compute its PDG

- Most analyses are included in the following 3 frameworks:
    - SCAF: https://github.com/PrincetonUniversity/SCAF
    - SVF: https://github.com/SVF-tools/SVF
    - LLVM: http://llvm.org

- NOELLE includes an extra alias analysis as well
  to capture corner cases that alias analyses above do not
    - We see alias analysis to be used by NOELLE, rather than for NOELLE to provide
    - Hence, when another alias infrastructure will capture them,
      this NOELLE's AA will be removed

Outline

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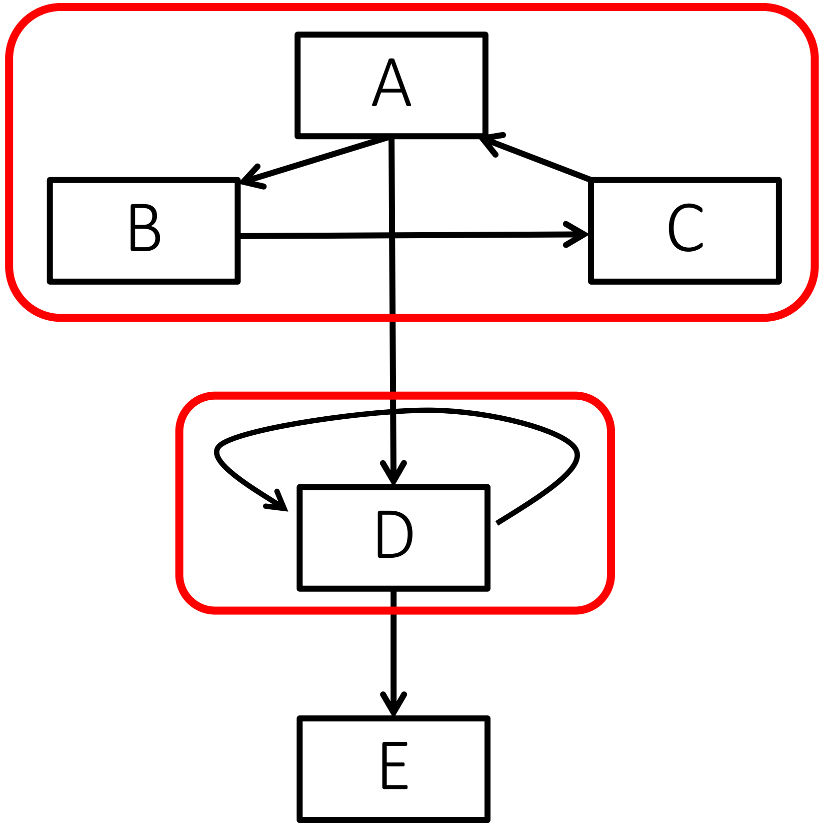
- Semantics of dependences

NOELLE’s Hierarchical SCCDAG

- From the PDG

- To the SCC identifications

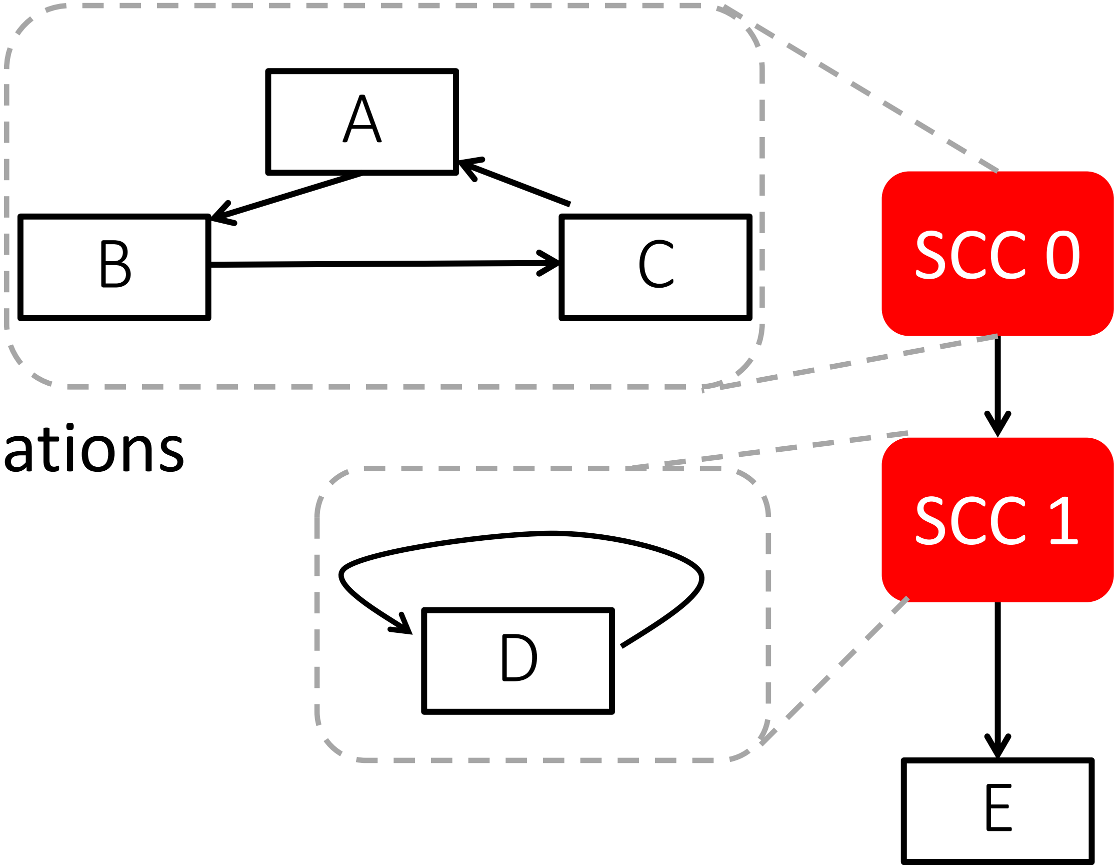


NOELLE’s Hierarchical SCCDAG

- From the PDG

- To the SCC identifications

- To the SCCDAG

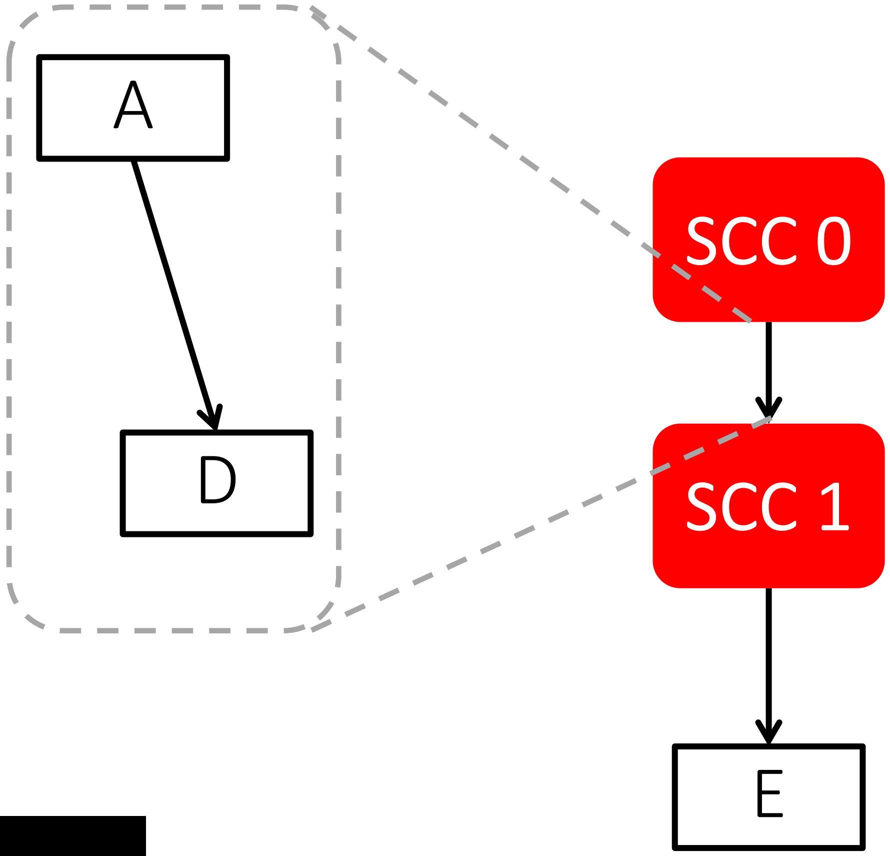


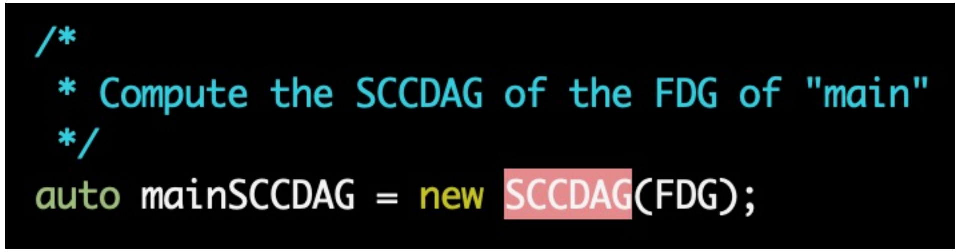
NOELLE’s Hierarchical SCCDAG

- From the PDG

- To the SCC identifications

- To the SCCDAG





```
/*
 * Compute the SCCDAG of the FDG of "main"
 */
auto mainSCCDAG = new SCCDAG(FDG);
```

Outline

- Program Dependence Graph at the instruction granularity

- SCCDAG

- Semantics of dependences

Dependences

- Control dependences
- Data dependences
    - Variable
    - Memory

Dependences

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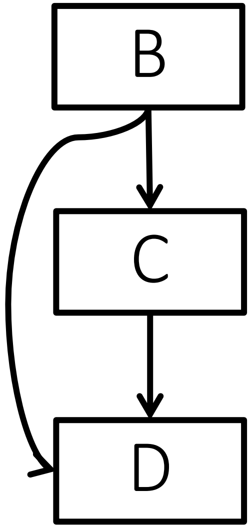
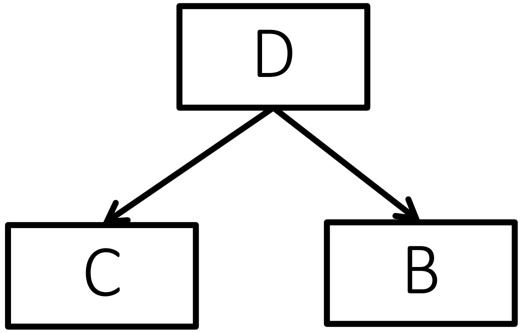
Post-Dominators

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



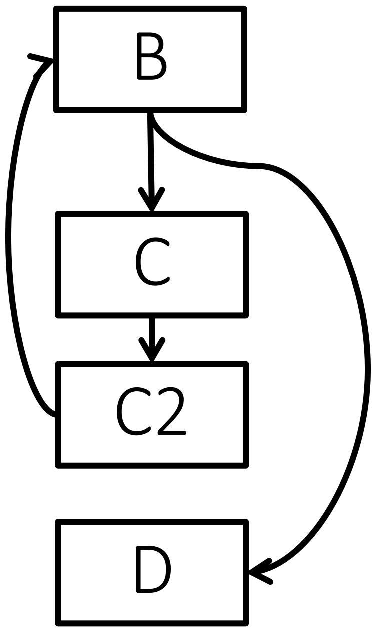
Immediate
post-dominator tree

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

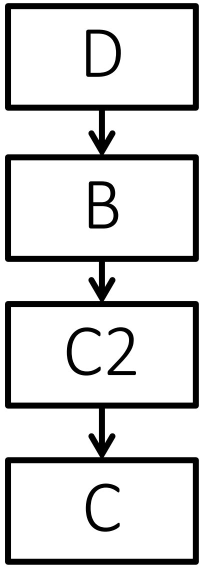
Control dependences

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

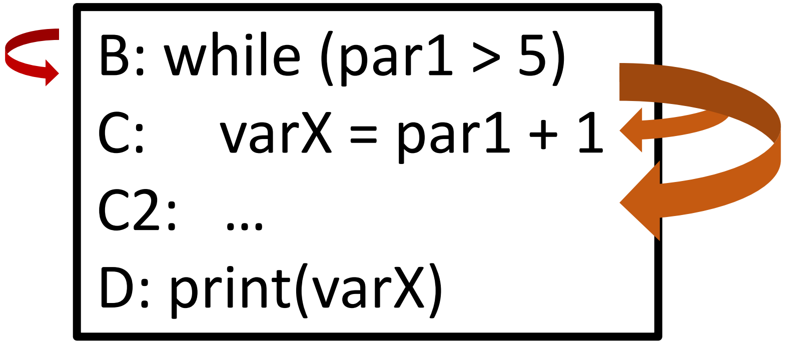
1. There is a path from X to Y such that every node in that path other than X is post-dominated by Y
2. X is not **strictly** post-dominated by Y



CFG



Immediate post-dominator tree



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

Dependences

- Control dependences
- Data dependences
  - Variable
  - Memory

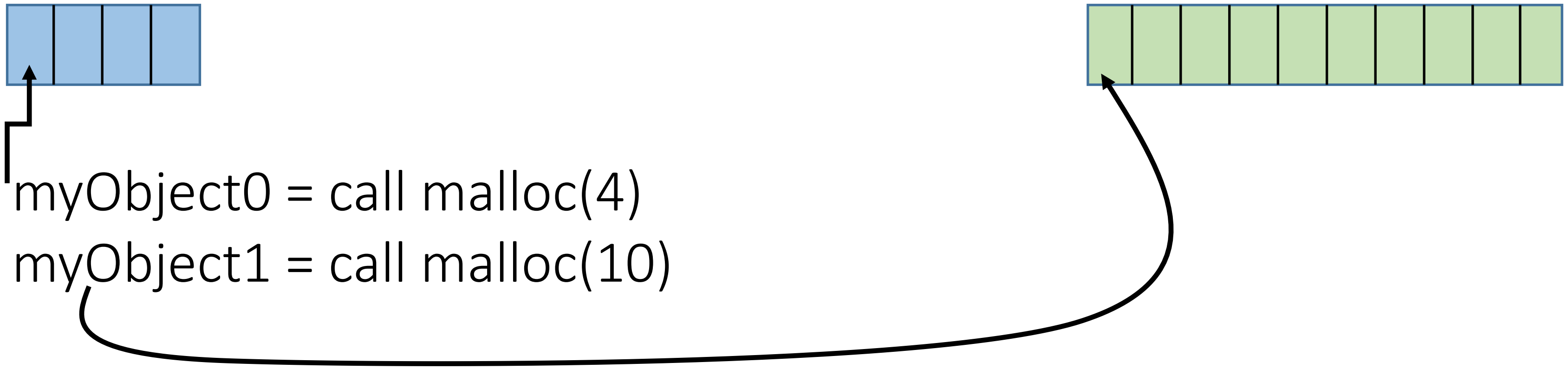
Data dependences

- A variable dependence is a def-use chain in LLVM
- A memory dependence from instruction i1 to instruction i2 exists iff [*]:
    - the footprint of operation i1 may-alias the footprint of i2 (alias);
    - at least one of the two instructions writes to memory (update);
    - there is a feasible path of execution P from i1 to i2 (feasible-path) such that no operation in P overwrites the common memory footprint (no-kill).

Footprint refers to the memory locations accessed (read or written)
by an instruction.

[*] Sotiris Apostolakis , Ziyang Xu , Zujun Tan , Greg Chan, Simone Campanoni, and David I. August
SCAF: A Speculation-Aware Collaborative Dependence Analysis Framework. PLDI 2020.

The (LLVM) memory model

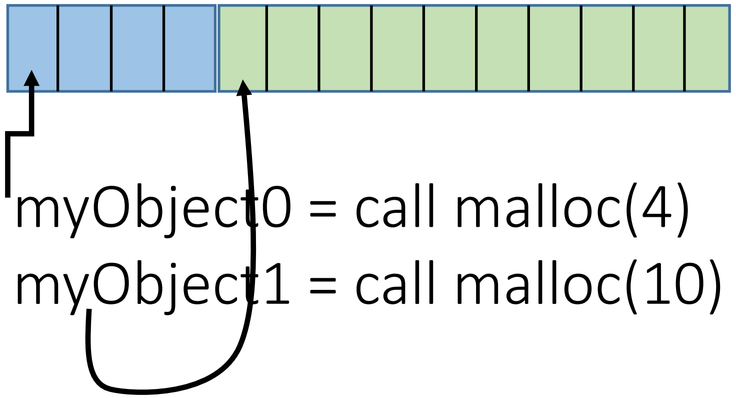


myObject0 = call malloc(4)
myObject1 = call malloc(10)

p = myObject0 + 4

Can p **alias** myObject1**?**

The (LLVM) memory model



```
myObject0 = call malloc(4)
myObject1 = call malloc(10)

p = myObject0 + 4
```

Can p **alias** myObject1**?**

Always have faith in your ability

Success will come your way eventually

Best of luck!