c⚙de analysis

and

transf⚙rmation

Dependences

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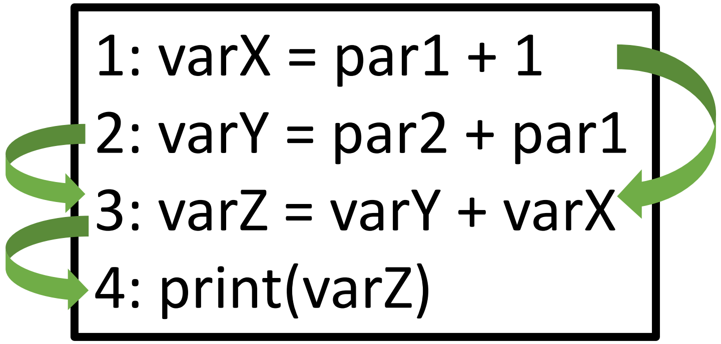
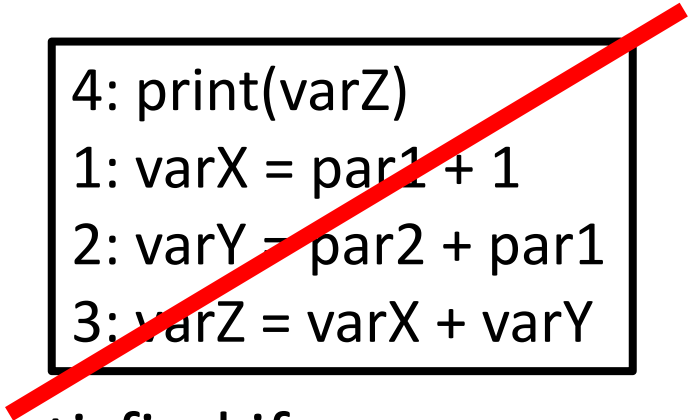
Dependences: the big picture

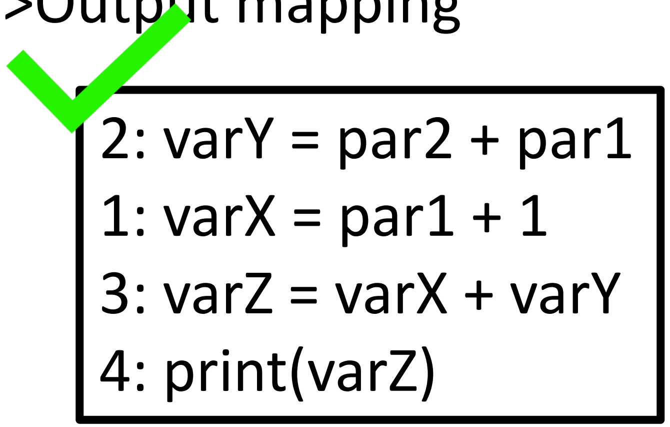
- Code transformations are designed to preserve the semantics of the code given as input
  - As defined earlier, semantics of a program is the Input=>Output mapping



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

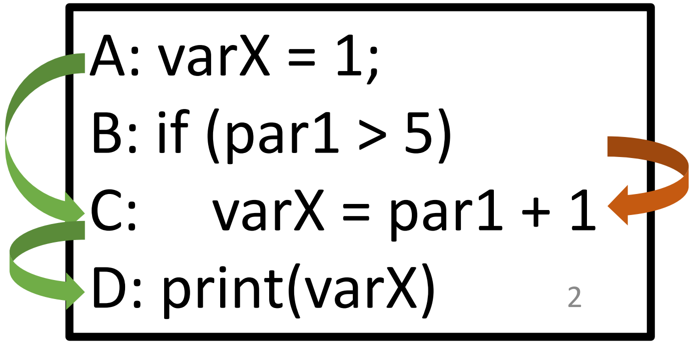


```
4: print(varZ)
1: varX = par1 + 1
2: varY = par2 + par1
3: varZ = varX + varY
```



```
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)
```

Outline

- Control dependences

- Data dependences

- Introduction to memory alias analysis

Control dependence intuition

- Dependence: C will be executed depending on B

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

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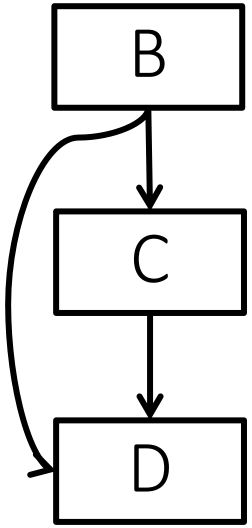
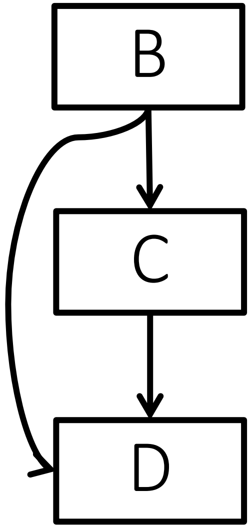



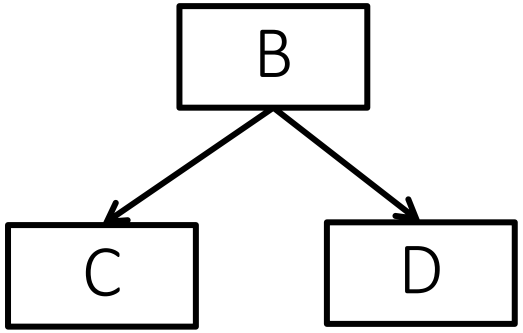
CFG

Dominators

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



CFG



Immediate dominator tree

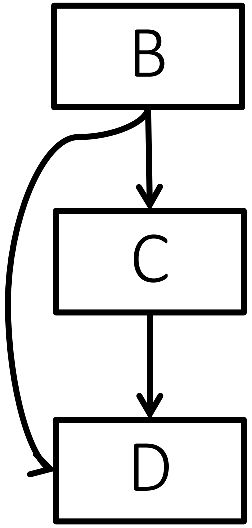
```
B: if (par1 > 5)
C:     varX = par1 + 1
D: print(varX)
```

Are dominators useful to identify the control dependence between C and B?

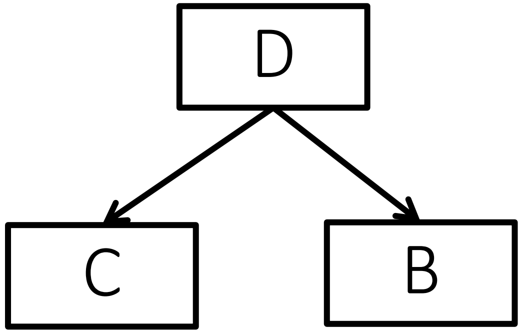
Post-Dominators

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)
```

How can we identify C and B with the post-dominator tree and the CFG?

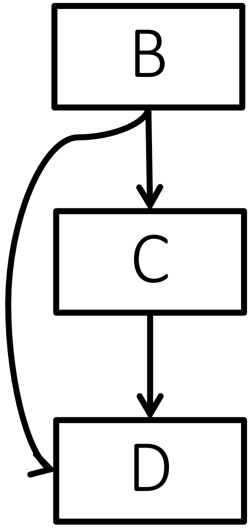
B determines whether C executes or not

Control dependence in our example

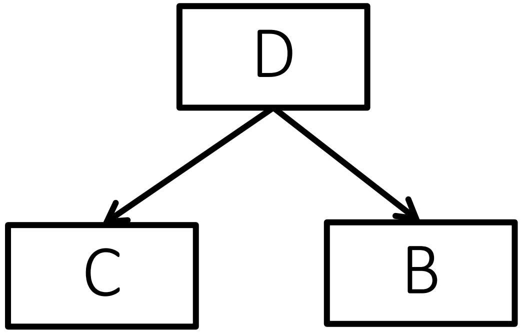
Node *C* is control-dependent on *B* because

1. C is the successor of B
2. C does not post-dominate B

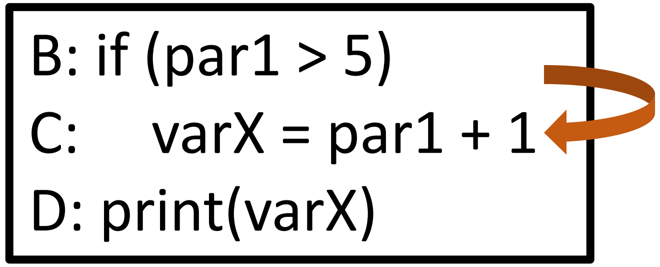
Do you see any problem?



CFG



Immediate post-dominator tree



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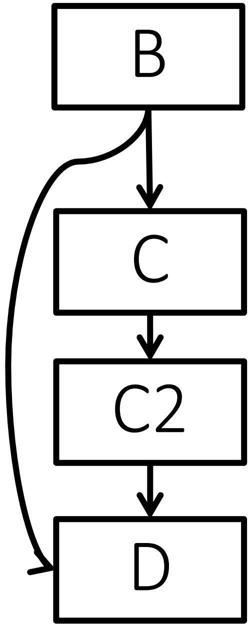
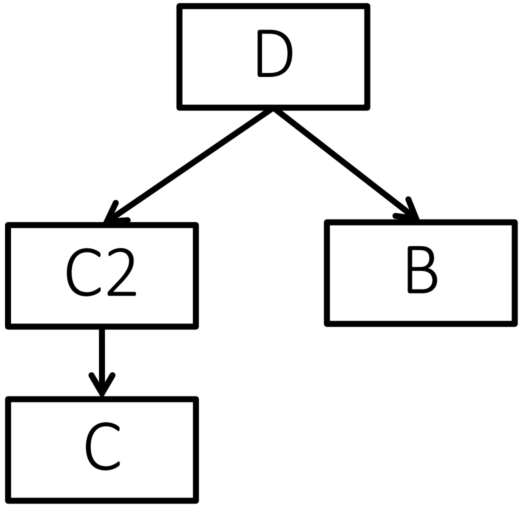
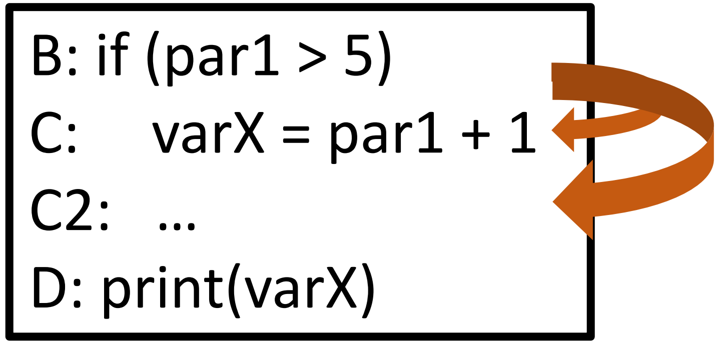


CFG



Immediate
post-dominator tree



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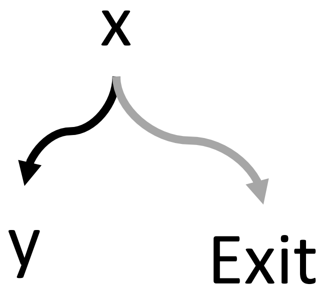
B: if (par1 > 5)
C:     varX = par1 + 1
C2:   ...
D: print(varX)
```

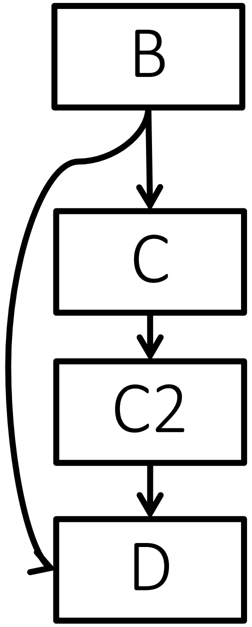
Why?

Control dependences (almost correct)

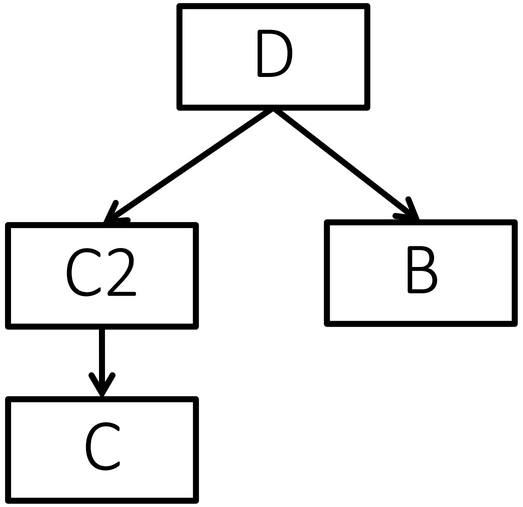
A node *Y* control-depends on another node *X* if and only if

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 post-dominated by Y

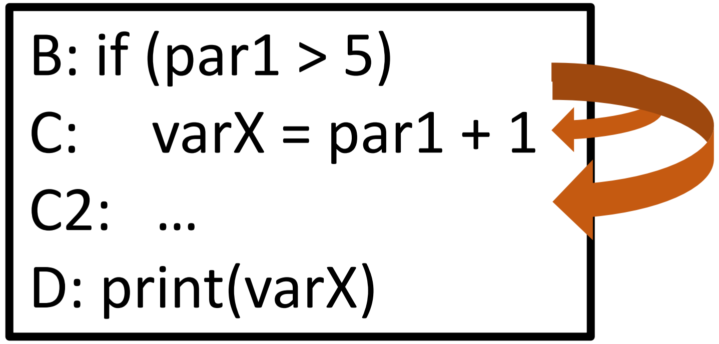




CFG



Immediate post-dominator tree



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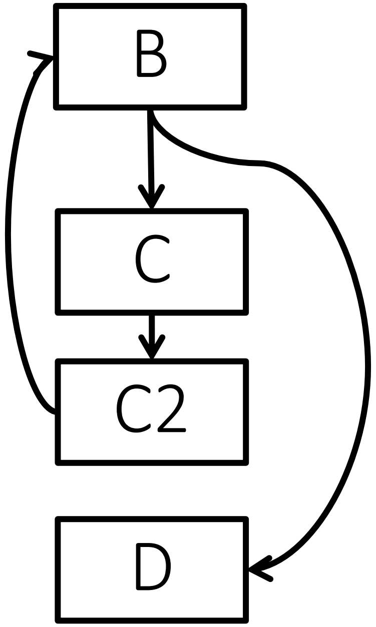
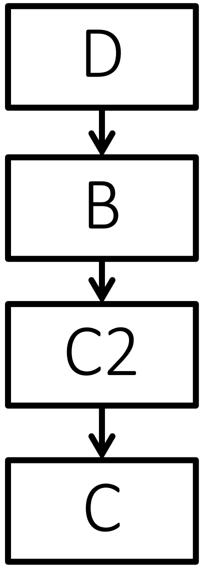
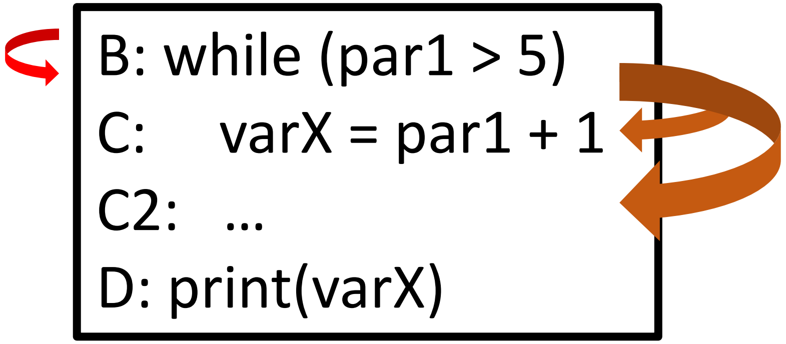


CFG



Immediate post-dominator tree

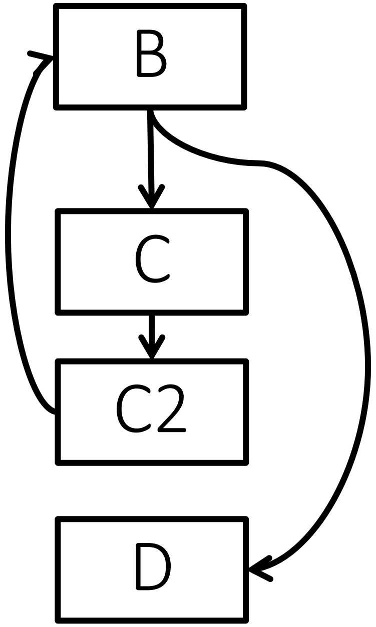


```
B: while (par1 > 5)
C:     varX = par1 + 1
C2:    ...
D: print(varX)
```

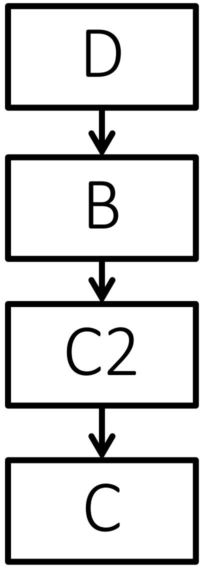
Control dependences

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

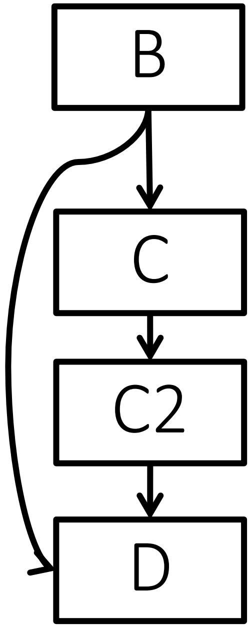


Immediate post-dominator tree

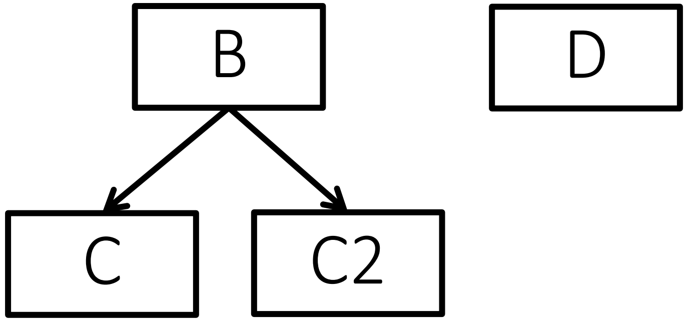
```
B: while (par1 > 5)
C:     varX = par1 + 1
C2:   …
D: print(varX)
```

Control dependence graph (CDG)

- Graph (N, E) where
  - N are basic blocks
  - Exist an edge (x,y) in E if and only if y control-depends on x



CFG



CDG

An use of CDG:

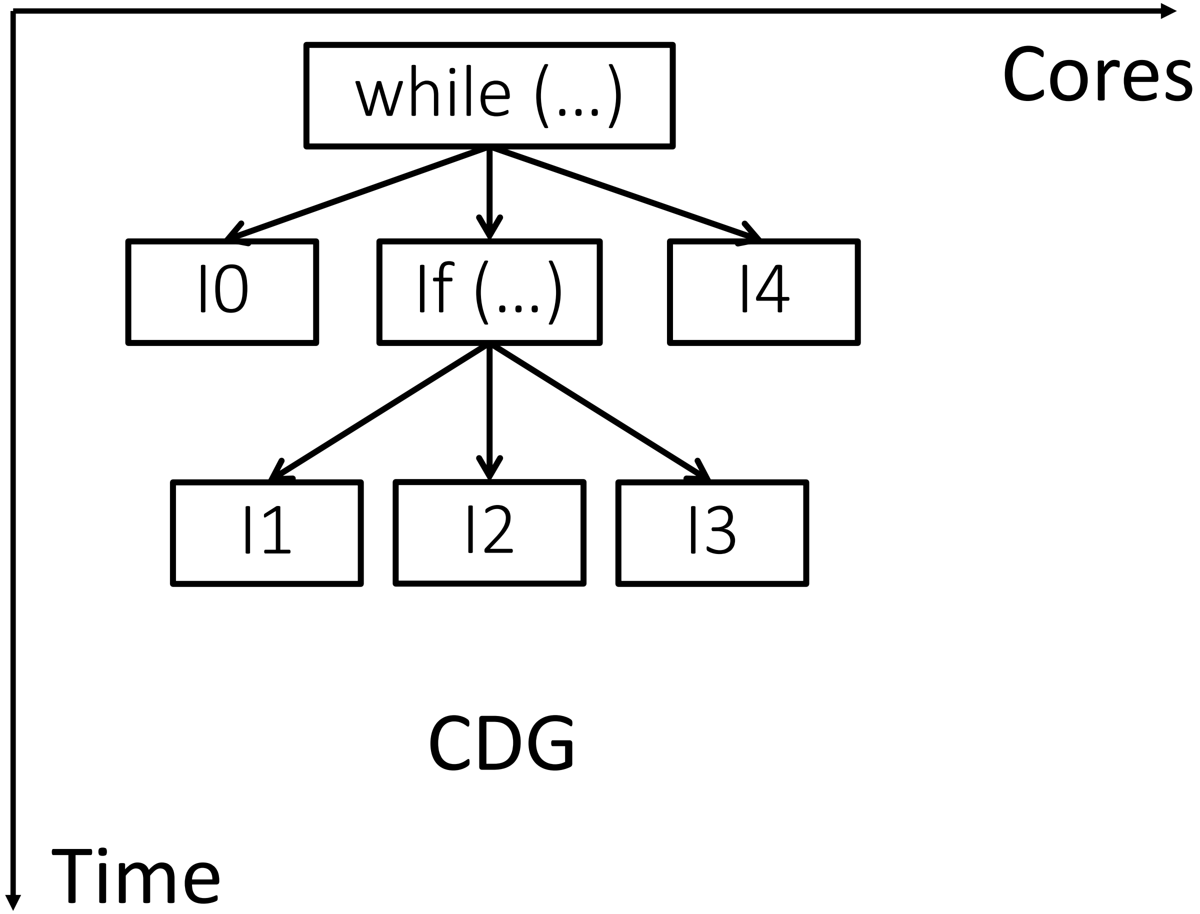
Sequential program: fixed order of execution

Goal: remove unnecessary order

Useful for parallelism

Extracting parallelism automatically

```
     while (…)
I0:    …
       if (…){
I1:        …
I2:        …
I3:        …
       }
I4:    …
    }
```



- Assuming
  - no data dependence
  - Infinite cores
- We want to minimize the wall time of our program

Control dependence graph

- The previous definition of control dependences

A node *X* is control-dependent 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 is post-dominated by Y
2. X is not strictly post-dominated by Y

- Naïve implementation:

  Iterate over all pair of instructions

  Check conditions 1 and 2 for each pair

  $O(N^2)$

- Can we do better?

Control dependence graph: algorithm

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
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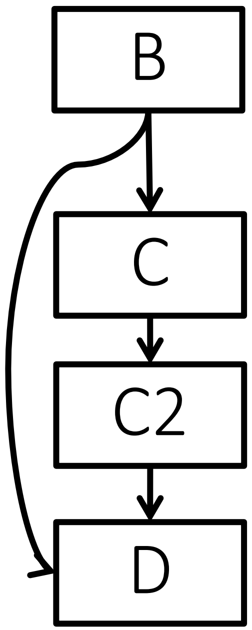
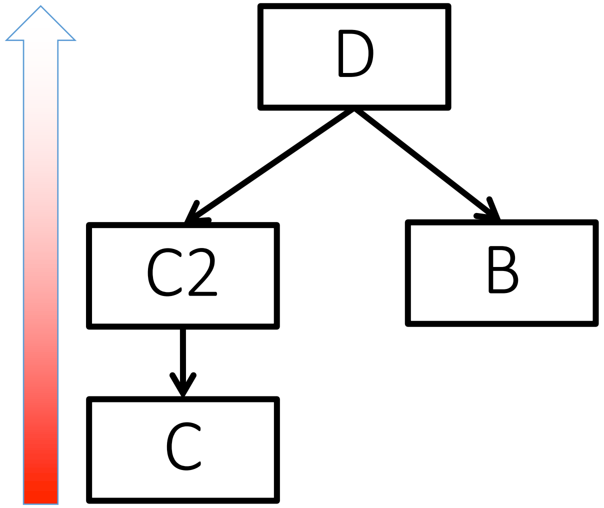
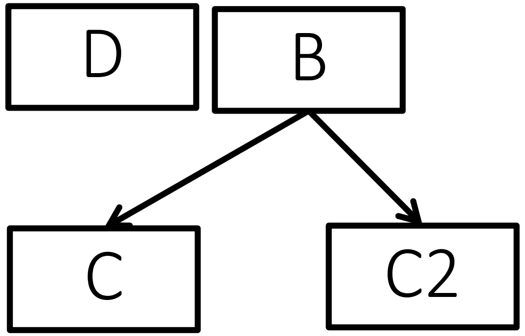


CFG



Immediate post-dominator tree



CDG

(B,C)
(B,C2)

How can we compute the CDG?

Outline

- Control dependences

- Data dependences

- Introduction to memory alias analysis

Data dependence

Three types of data dependence (assuming int a,b,c):

- Flow (True) dependence : read-after-write

```
a = c * 10;
b = 2 * a + c;
```

- Anti Dependency: write-after-read

```
a = b* 4+ c;
c = b + 40;
```

- Output Dependence: write-after-write

```
 a = b *c ;
a = b + c + 10;
```

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!

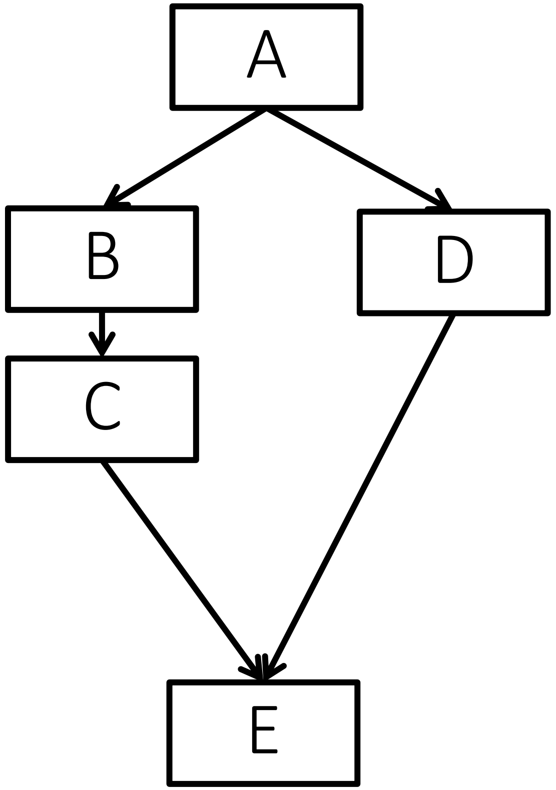
Data dependence graph (DDG)

- Graph (N, E) where
  - N are instructions
  - Exist an edge (x,y) in E if and only if y is data dependent on x

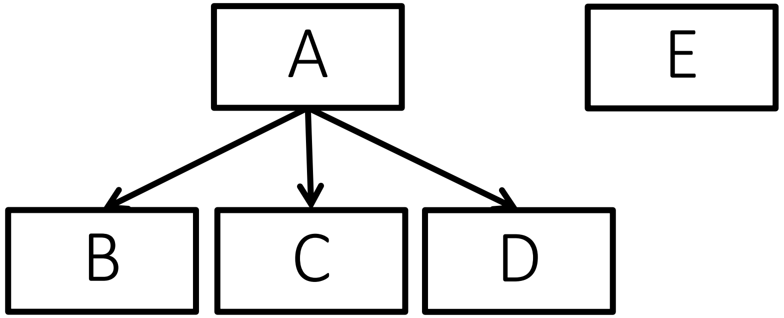
Differences between CDG and DDG

- Granularity
- Structure vs. content

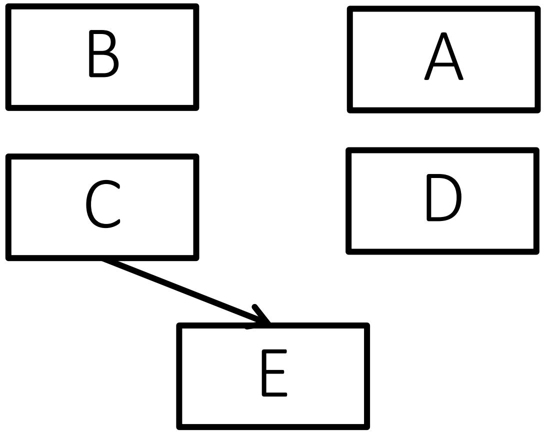
Dependence example



CFG



CDG



DDG

What are the possible executions that preserve the original semantics of the program?

A B C E   A D E

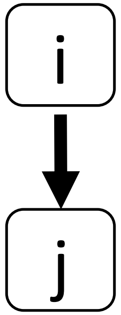
A C B E   A E D   A C E B

Dependence descriptors

- Data vs. control
- RAW, WAR, WAW
- …

Loop-carried data dependences

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



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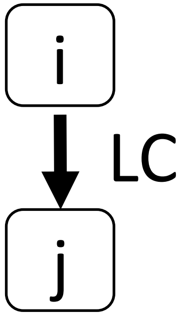
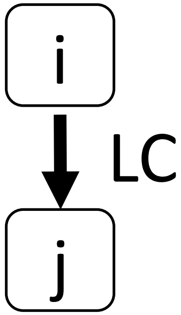
```



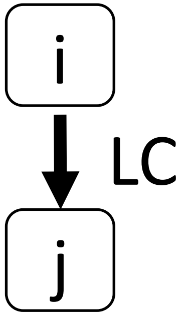
Loop-carried data dependences

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



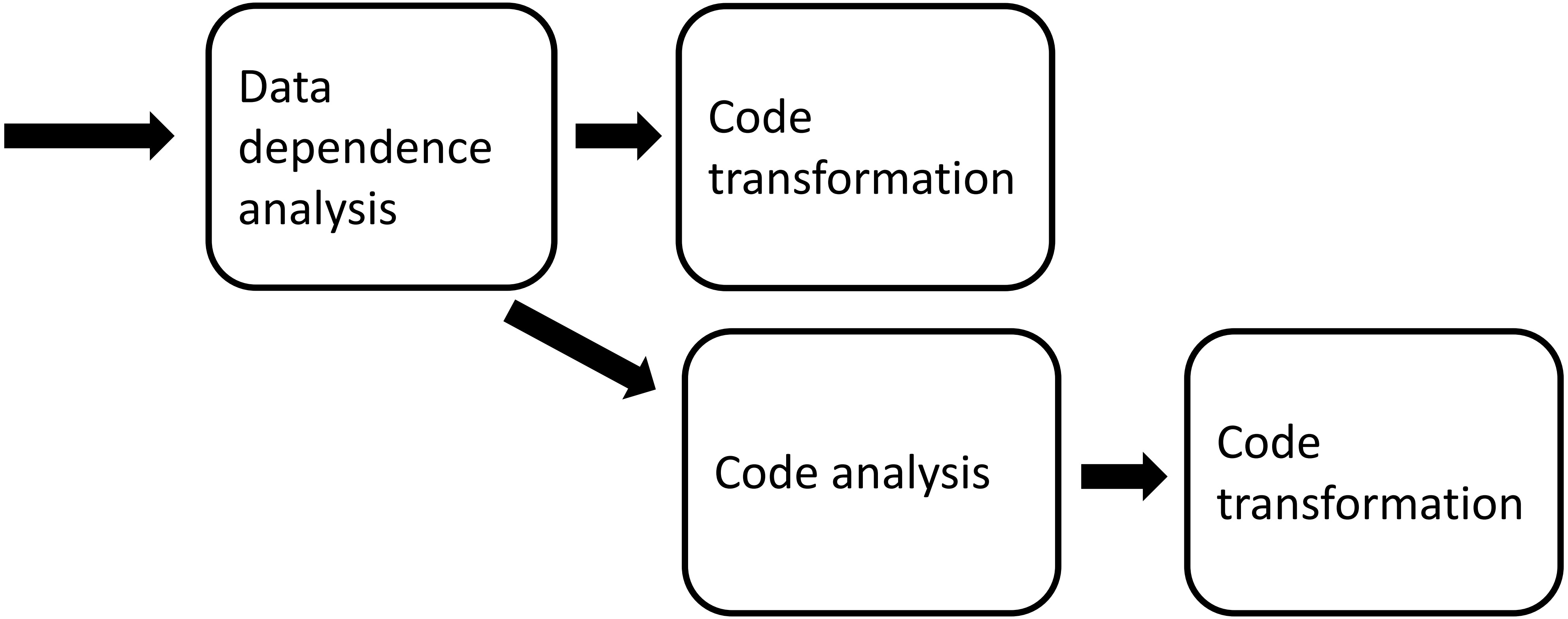
Distance =1

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



Distance =2

Data dependence analysis and others



Data dependence analysis

Code transformation

Code analysis

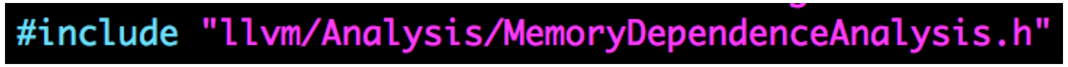
Code transformation

(Variable) Data dependences in LLVM

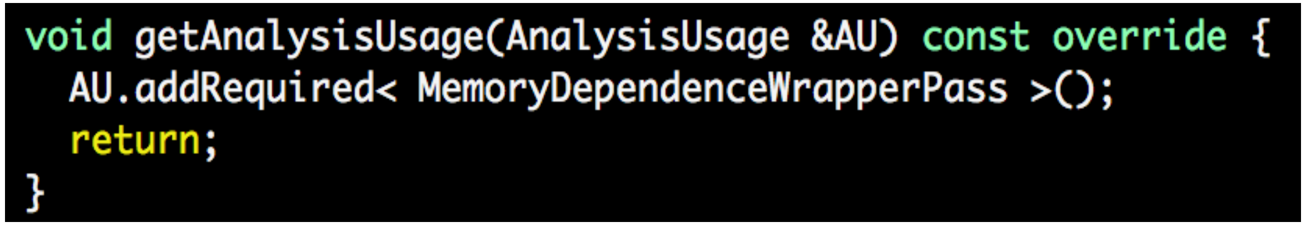
Any idea?

(Memory) Data dependences in LLVM

- Memory data dependences are computed by MemoryDependenceAnalysis

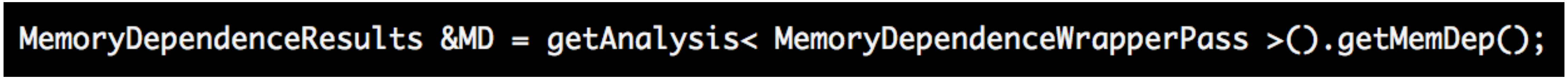


```
#include "llvm/Analysis/MemoryDependenceAnalysis.h"
```



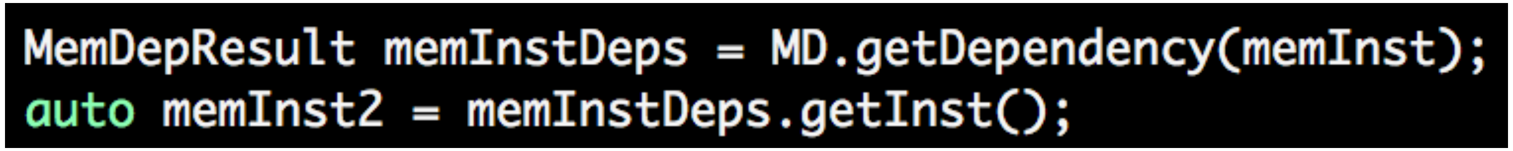
```
void getAnalysisUsage(AnalysisUsage &AU) const override {
  AU.addRequired< MemoryDependenceWrapperPass >();
  return;
}
```

- To get the output of the data dependence analysis:



```
MemoryDependenceResults &MD = getAnalysis< MemoryDependenceWrapperPass >().getMemDep();
```

- To get a dependency



```
MemDepResult memInstDeps = MD.getDependency(memInst);
auto memInst2 = memInstDeps.getInst();
```

Program dependence graph

- Program Dependence Graph = Control Dependence Graph +
  Data Dependences

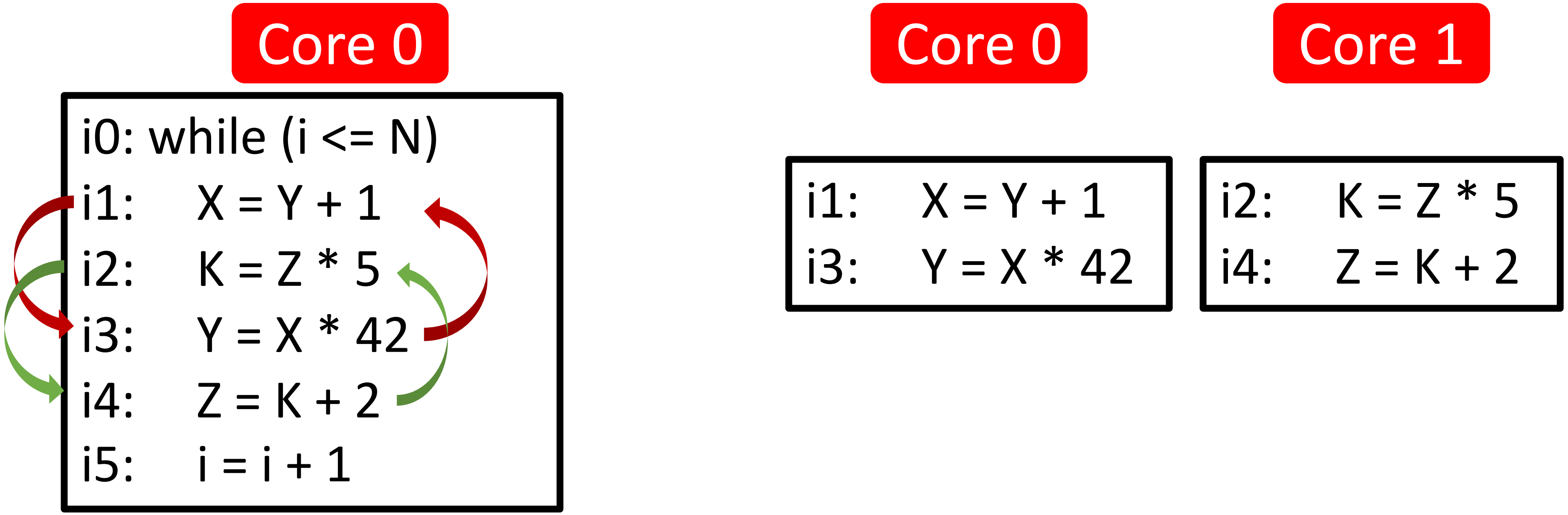
- Facilitates performing most traditional optimizations
  - Constant folding, scalar propagation, common subexpression elimination, code motion, strength reduction

- 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
```

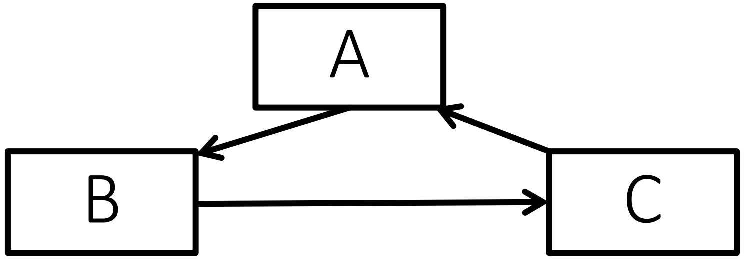
Core 1

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

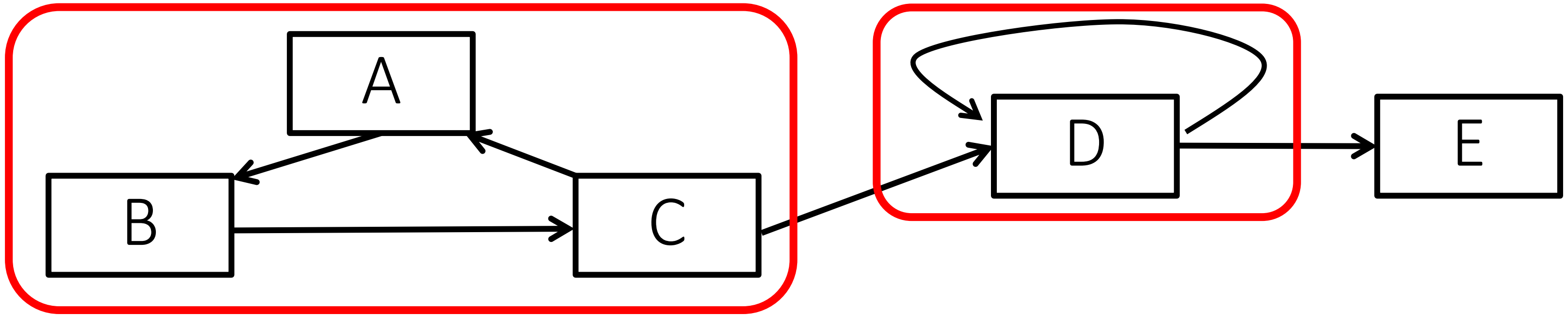
Different colors <-> different cycles in the PDG => different cores

Strongly Connected Component (SCC)

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



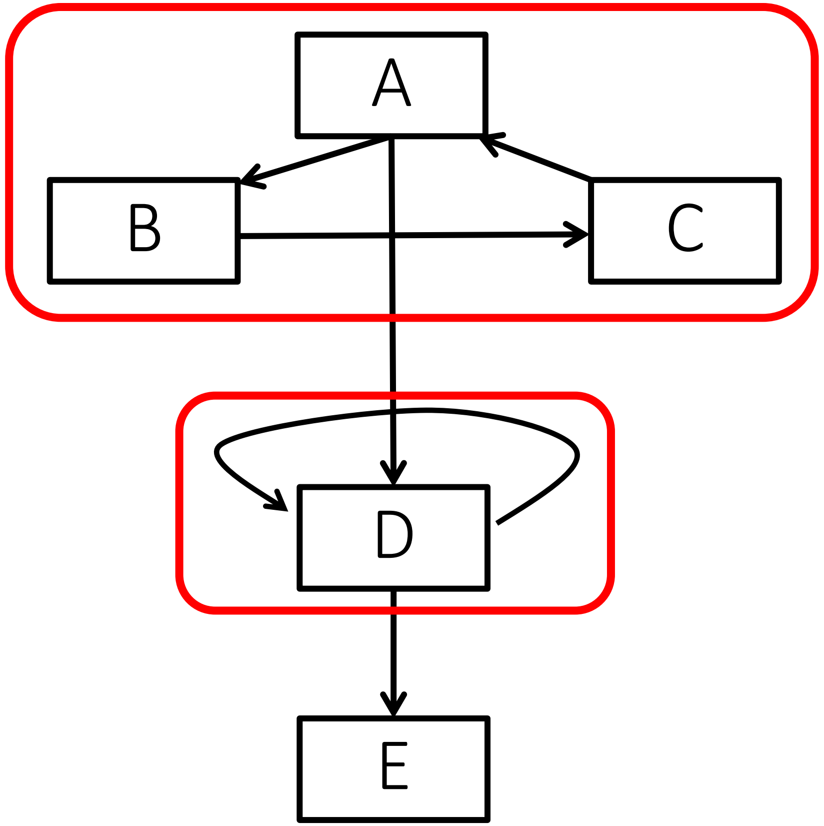
- A strongly connected component (**SCC**) of a directed graph is a maximal strongly connected subgraph



SCCDAG

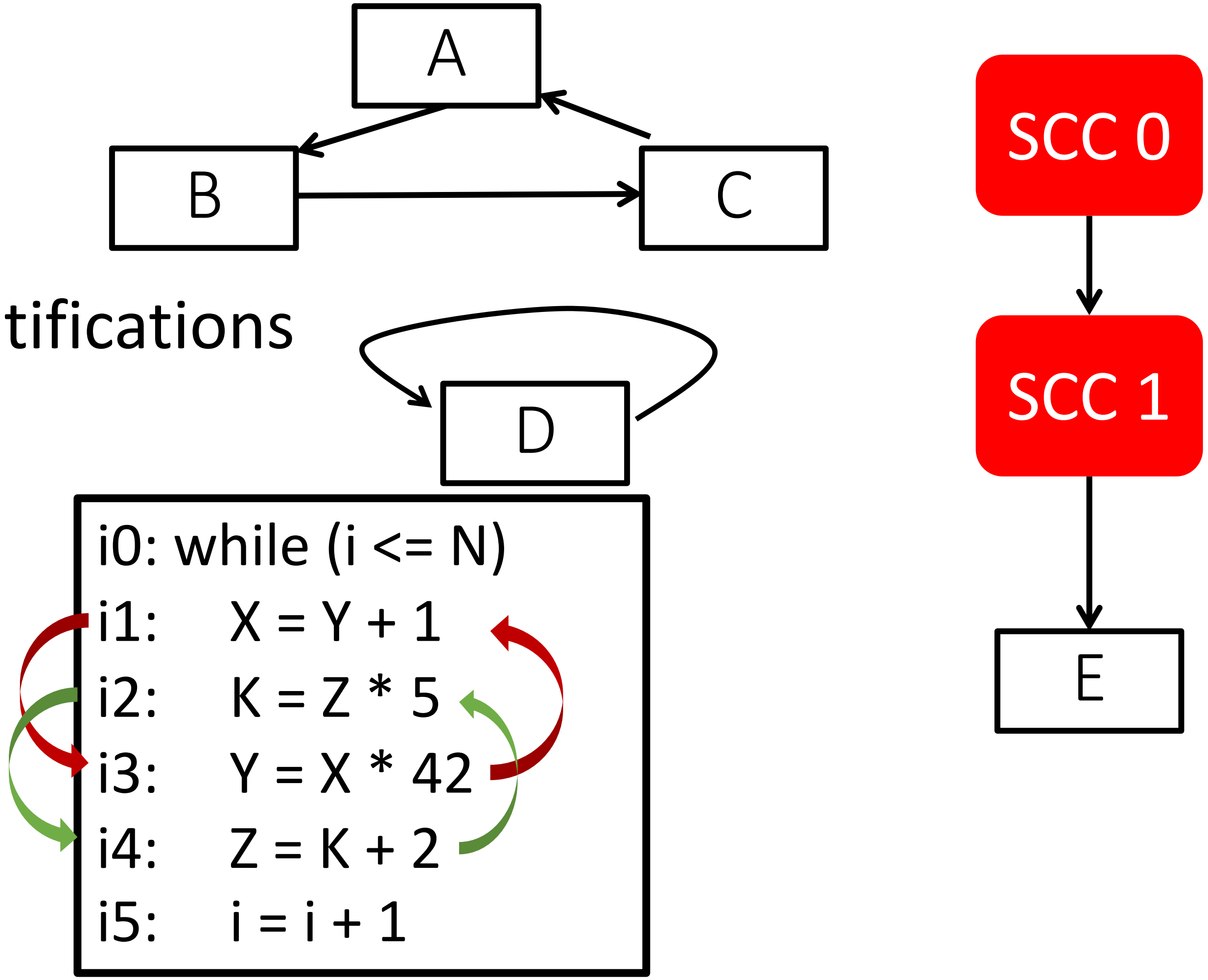
- From the PDG

- To the SCC identifications



SCCDAG

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



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i3:     Y = X * 42
i4:     Z = K + 2
i5:     i = i + 1
```

Identify SCCs

- Tarjan's algorithm ← In practice, this is faster
    - It utilizes the property that nodes of a strongly connected component form a subtree in the DFS spanning tree of the graph
    - Complexity: O(|N| + |E|)
- Kosaraju's algorithm
    - It utilizes the property that the transpose graph (the same graph with the direction of every edge reversed) has the same strongly connected components as the original graph
    - Performs two DFSs on the graph
    - It is similar to the method for finding the topological sorting
    - Complexity: O(|N| + |E|)

Identify SCCs in LLVM (Tarjan’s algorithm)

- Two template APIs to iterate over SCCs of a graph G: scc_begin() and scc_end()

```
for (auto sccI = scc_begin(pdg); sccI != scc_end(pdg); ++sccI) {
    auto const &scc = *sccI;
}
```

- These APIs assume the method getEntryNode() can be called from the object given as input
- The return type of getEntryNode() set the type of scc

  E.g., if we have the following method for our pdg:MyNodeT * getEntryNode ()

  Then scc is of type std::vector<MyNodeT *> and therefore

  const std::vector<MyNodeT *> &scc = *sccI;

Outline

- Control dependences
- Data dependences
- Introduction to memory alias analysis

Memory alias analysis: the problem

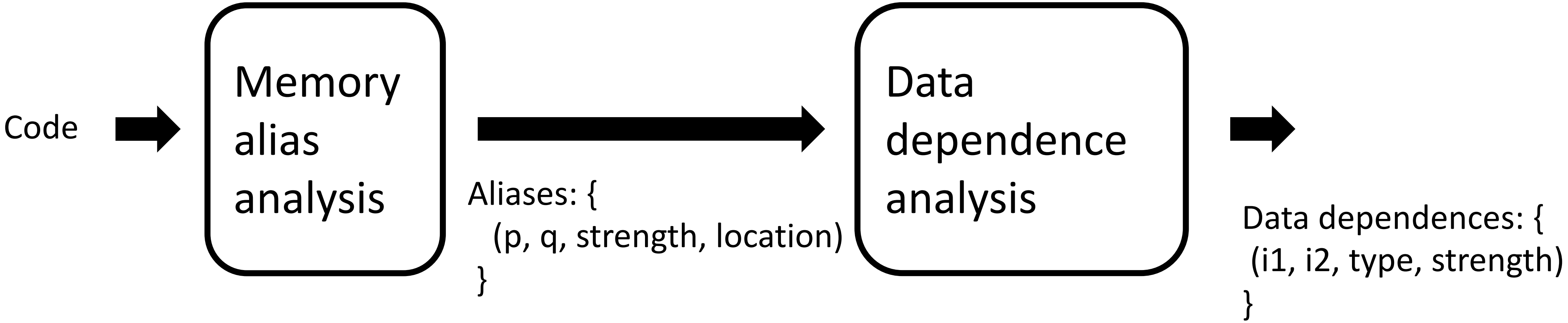
- We want to
  - Execute *j* in parallel with *i* (extracting parallelism)
  - Move *j* before *i* (code scheduling)
- Does *j* depend on *i* ?

```
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/data dependence analysis



Code

Memory alias analysis

Aliases: {
  (p, q, strength, location)
}

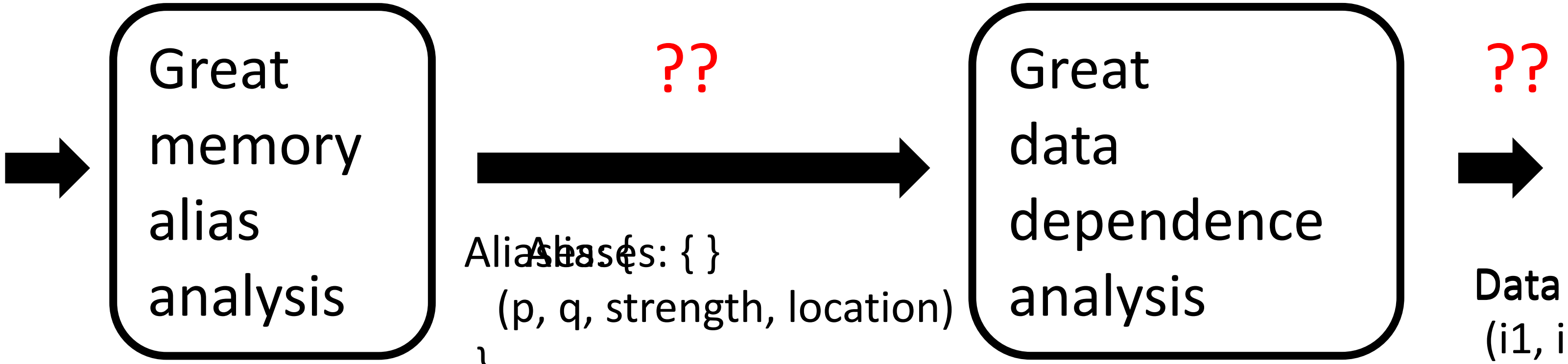
Data dependence analysis

Data dependences: {
 (i1, i2, type, strength)
}

Memory alias/data dependence analysis

Can we optimize the code knowing these dependences?

```
~~1: *p1 = …~~
2: *p2 = …
3: v1 = *p2
```

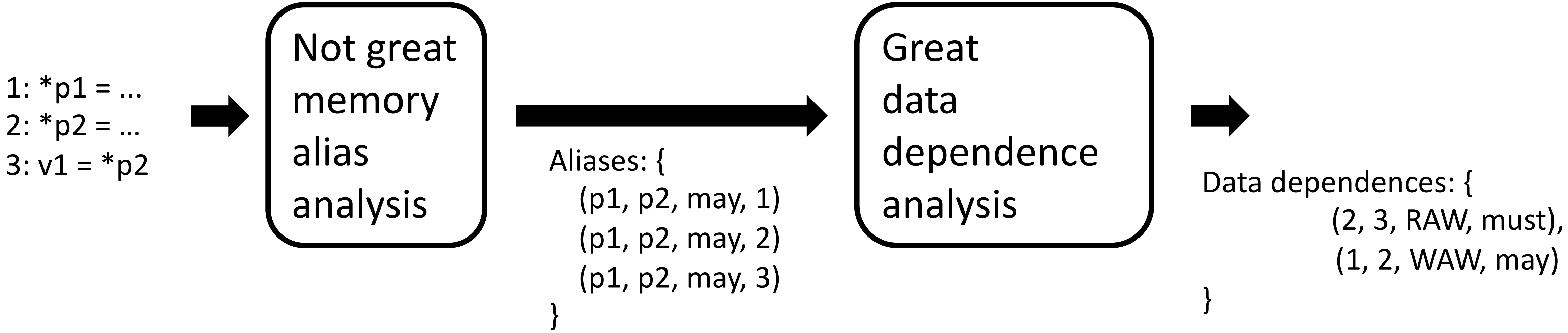


Aliases {
Aliases: { }
(p, q, strength, location)
}

Data dependences: {
(i1, i2, type, strength, must)
(2, 3, RAW)
}

Oracle:
p2 and p1 points to different memory locations always

Memory alias/data dependence analysis



```
1: *p1 = …
2: *p2 = …
3: v1 = *p2
```

Not great memory alias analysis

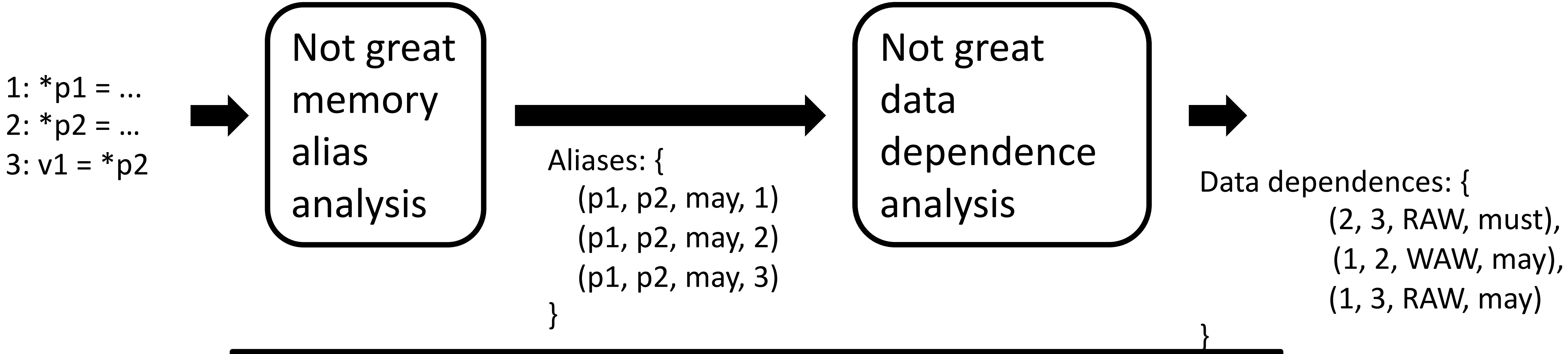
```
Aliases: {
   (p1, p2, may, 1)
   (p1, p2, may, 2)
   (p1, p2, may, 3)
}
```

Great data dependence analysis

```
Data dependences: {
                (2, 3, RAW, must),
                (1, 2, WAW, may)
}
```

Oracle:
p2 and p1 points to different memory locations always

Memory alias/data dependence analysis



```
1: *p1 = ...
2: *p2 = ...
3: v1 = *p2
```

Not great memory alias analysis

```
Aliases: {
    (p1, p2, may, 1)
    (p1, p2, may, 2)
    (p1, p2, may, 3)
}
```

Not great data dependence analysis

```
Data dependences: {
            (2, 3, RAW, must),
            (1, 2, WAW, may),
            (1, 3, RAW, may)
}
```

Oracle:
p2 and p1 points to different memory locations always

Analysis output:
Everything depends on everything else

Memory alias/data dependence analysis

Inaccuracies on either memory alias analysis
or data dependence analysis
leads to "apparent" dependences

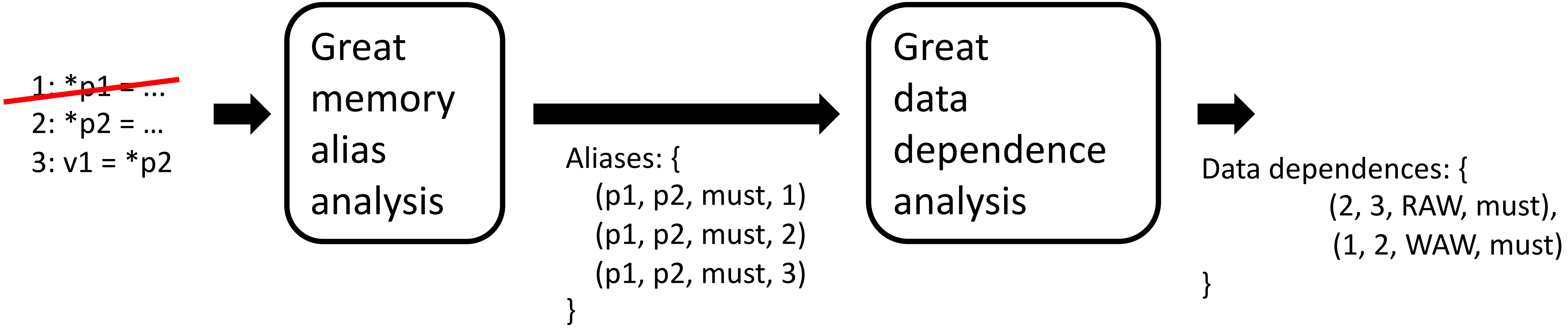
- **More constraints on code transformations**
- **Reduce the aggressiveness of code transformations**
- **Reduce performance obtained**

Oracle:
p2 and p1 points to different memory locations always

Analysis output:
Everything depends on everything else

Memory alias/data dependence analysis

Can we optimize the code knowing these dependences?



~~1: *p1 = …~~
2: *p2 = …
3: v1 = *p2

Great memory alias analysis

Aliases: {
(p1, p2, must, 1)
(p1, p2, must, 2)
(p1, p2, must, 3)
}

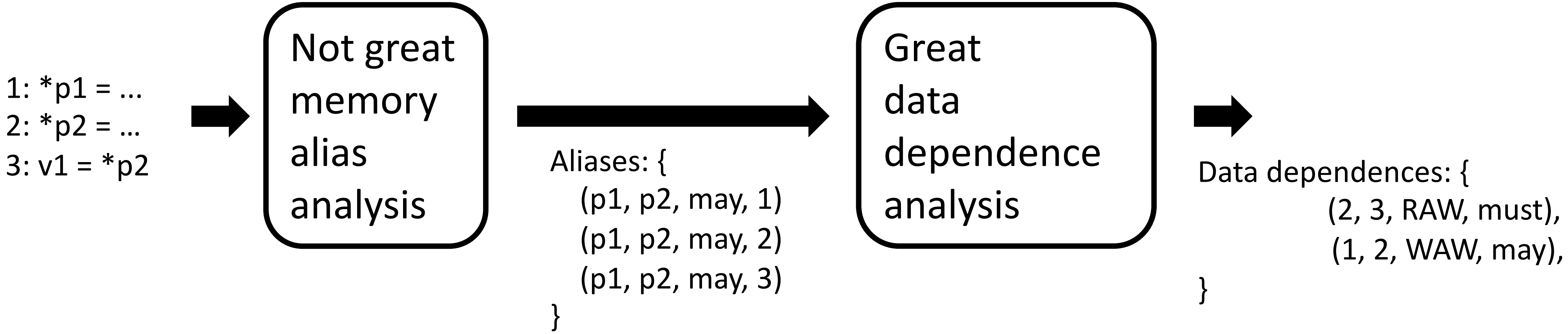
Great data dependence analysis

Data dependences: {
(2, 3, RAW, must),
(1, 2, WAW, must)
}

Oracle:
p2 and p1 points to the same memory location always

Memory alias/data dependence analysis

We cannot delete instruction 1



```
1: *p1 = …
2: *p2 = …
3: v1 = *p2
```

Not great memory alias analysis

```
Aliases: {
    (p1, p2, may, 1)
    (p1, p2, may, 2)
    (p1, p2, may, 3)
}
```

Great data dependence analysis

```
Data dependences: {
              (2, 3, RAW, must),
              (1, 2, WAW, may),
}
```

Oracle:
p2 and p1 points to the same memory location always

Memory alias/data dependence analysis

Useless output

- **Alias analysis:**
  a pointer may alias to another one
- **Data dependence analysis:**
  an instruction may depend on another one

… may …

Memory alias/data dependence analysis and code analysis/transformation

Code analysis and transformation

that rely on memory alias analysis
and/or data dependence analysis

must be correct

independently with the accuracy of
memory alias analysis
and/or data dependence analysis

Always have faith in your ability

Success will come your way eventually

Best of luck!