Analyzing and Transforming Native Code

Applied Static Analysis 2016

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Parameter Data-Flow Analysis

naive version

- Idea: Ignore control flow, path conditions, and calling context
- Iterate over instructions and see what happens

exercise 6.6

Parameter Data-Flow Analysis

naive version

`%tmp = alloca i32, align 4`	`%n`
`%tmp1 = alloca i32, align 4`	`%n`
`store i32 %n, i32* %tmp1, align 4`	`%n, %tmp1`
`%tmp2 = load i32, i32* %tmp1, align 4`	`%n, %tmp1, %tmp2`
`%tmp3 = icmp eq i32 %tmp2, 0`	`%n, %tmp1, %tmp2`
`br i1 %tmp3, label %bb4, label %bb5`	`%n, %tmp1, %tmp2`
`store i32 0, i32* %tmp`	`%n, %tmp1, %tmp2`
`br label %bb17`	`%n, %tmp1, %tmp2`
`%tmp6 = load i32, i32* %tmp1, align 4`	`%n, %tmp1, %tmp2, %tmp6`

exercise 6.6

naive version

Parameter Data-Flow Analysis

`exercises/ParameterFlow/`

- Iterate over all arguments of a function

  ```
  for(Argument &a : f.getArgumentList())
  ```

- Implement an `InstVisitor` for all relevant instructions

  ```
  struct FlowIV : public InstVisitor<FlowIV>
  ```

- Store tracked `Value` instances in a `DenseSet`

  ```
  DenseSet<Value*> trackedValues;
  ```

exercise 6.6

Parameter Data-Flow Analysis

naive version

`exercises/ParameterFlow/`

- Implement handler for all instructions relevant

```
void visitBinaryOperator(BinaryOperator &I) {
  Value *op1 = I.getOperand(0);
  Value *op2 = I.getOperand(1);

  if (isTracked(op1) || isTracked(op2)) {
     addTrackedValue(I);
  }
}
```

exercise 6.6

Parameter Data-Flow Analysis

naive version

- What are the problems of this approach?
- Is the result correct/sound?
- Is the result precise?

exercise 6.6

Control-Flow Sensitivity

- Consider this example:

```
int doStuff(int n) {
   int result = 0;
   if (false) {
      result = n;
   }
   return result;
}
```

- Does `n` flow to `result`?

Making the Analysis Control-Flow Sensitive

- Recall the following:

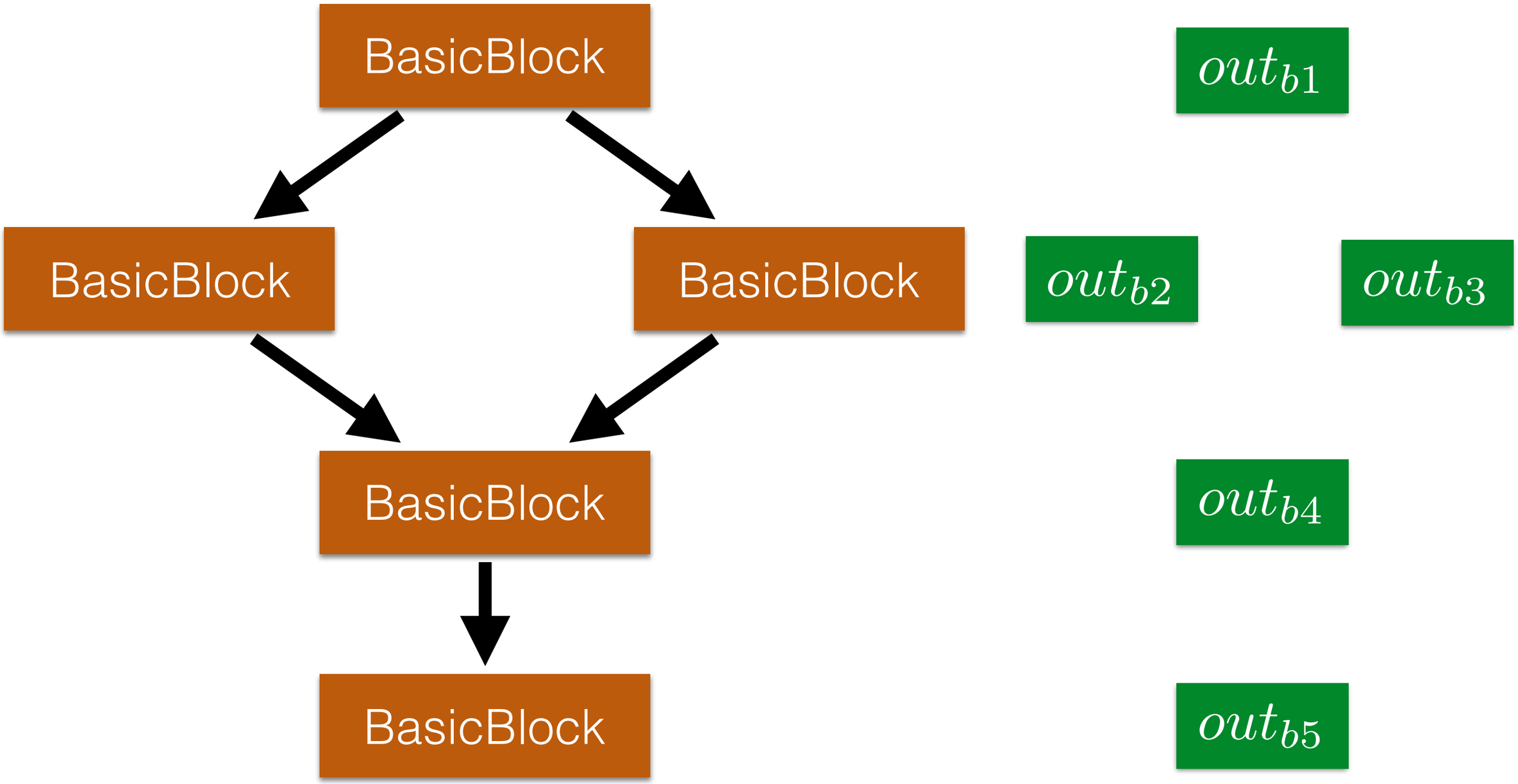
$$out_b = trans_b(in_b)$$

$$in_b = join_{p \in pred_b}(out_p)$$

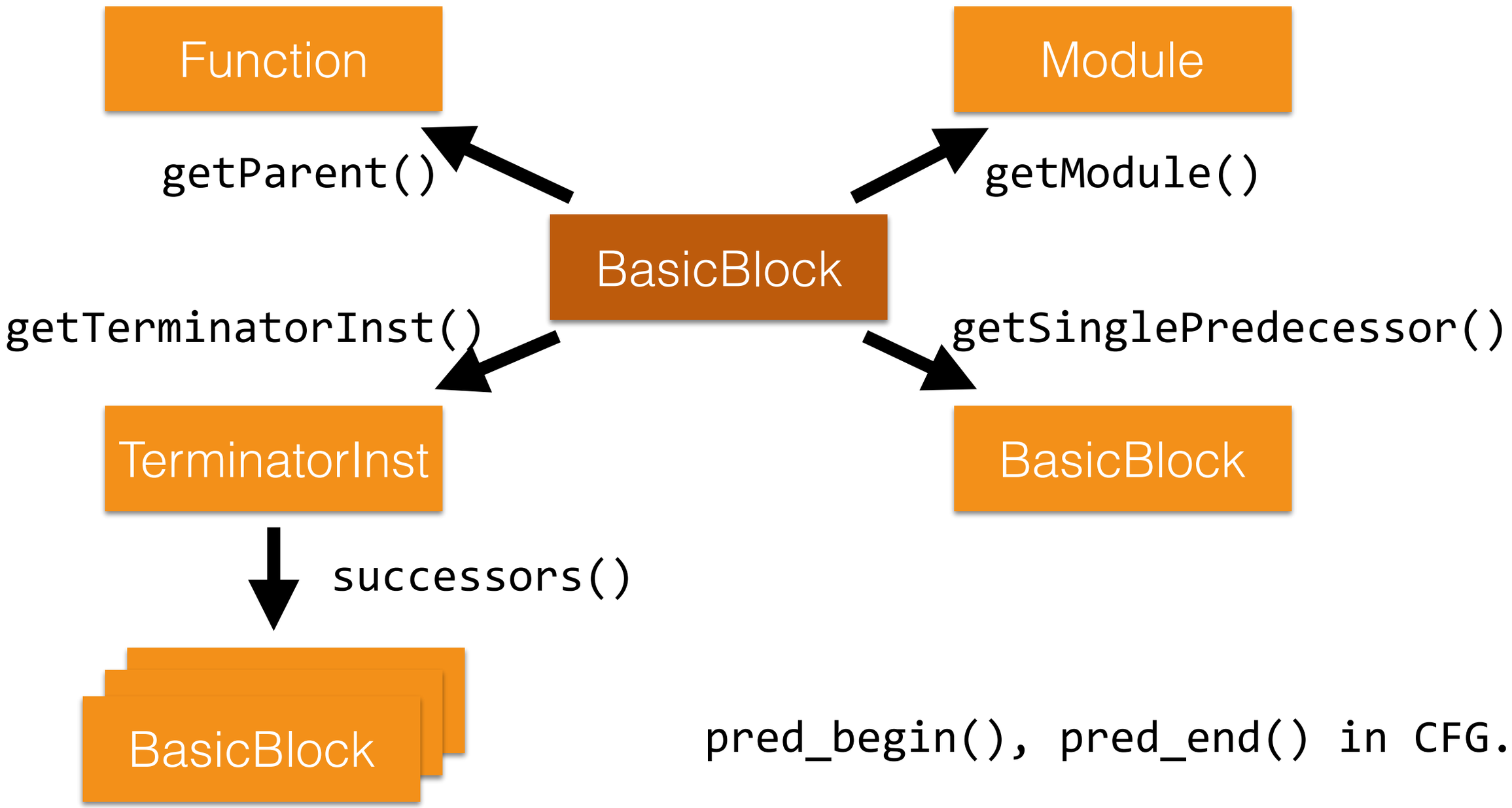
- This is exactly what we want:
  - basic block separated
  - output is the translation of the input
  - joined output of predecessors is input the next

exercise 7.1

Making the Analysis Control-Flow Sensitive

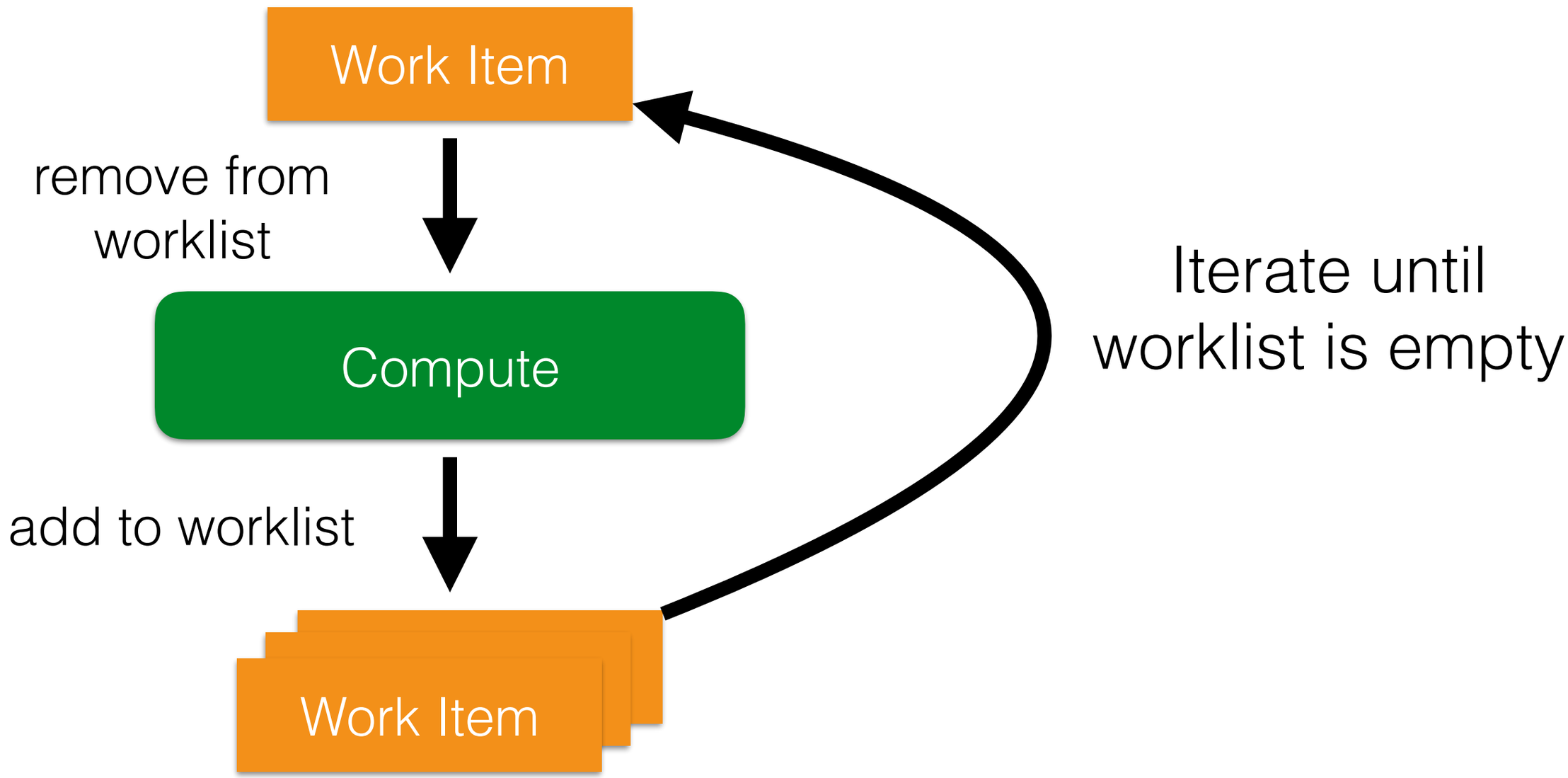


Basic Block



pred_begin(), pred_end() in CFG.h

Worklist Algorithms



Parameter Data-Flow Analysis

flow-sensitive version

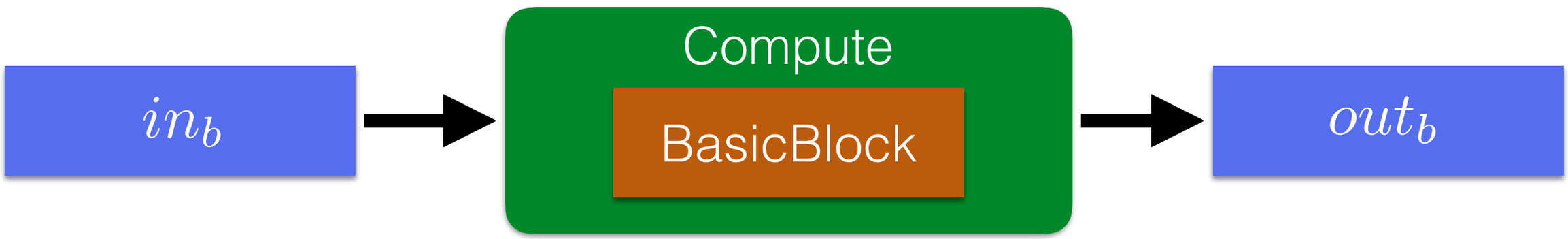
Standard pair

Incoming Tracked Values

```
std::vector<std::pair<BasicBlock*, DenseSet<Value*>>> worklist;
```

Standard vector data structure

Basic block to be processed



Parameter Data-Flow Analysis

flow-sensitive version

Computing the initial seed

```
for (BasicBlock &bb : f) {
  if (!hasPredecessor(&bb)) {
    DenseSet<Value*> incomingValues;
    incomingValues.insert(&a);
    worklist.push_back(std::make_pair(&bb, incomingValues));
  }
}

// […]
bool hasPredecessor(BasicBlock* bb) {
  if (pred_begin(bb) != pred_end(bb)) return true;
  return false;
}
```

Get all BasicBlocks w/o predecessors

Assume the argument as incoming

Add pair to work list

End and begin pointers differ

exercise 7.1

Parameter Data-Flow Analysis

flow-sensitive version

Worklist processing

```
while(!worklist.empty()) {
  std::pair<BasicBlock*, DenseSet<Value*>> current = worklist.back();
  worklist.pop_back();

  FlowIV flowVisitor;
  for (Value *v : current.second)
    flowVisitor.addTrackedValue(v);
  flowVisitor.visit(current.first);
  DenseSet<Value*> outgoingTracked = flowVisitor.getCurrentlyTrackedValues();

  TerminatorInst *blockTi = current.first->getTerminator();
  if (blockTi) {
    for(BasicBlock *succ : blockTi->successors()) {
      worklist.push_back(std::make_pair(succ, outgoingTracked));
    }
  }
}
```

Get the current item and pop it from the worklist

Reuse the FlowIV from before

Add initial values

Compute outgoing values

Iterate over successor block

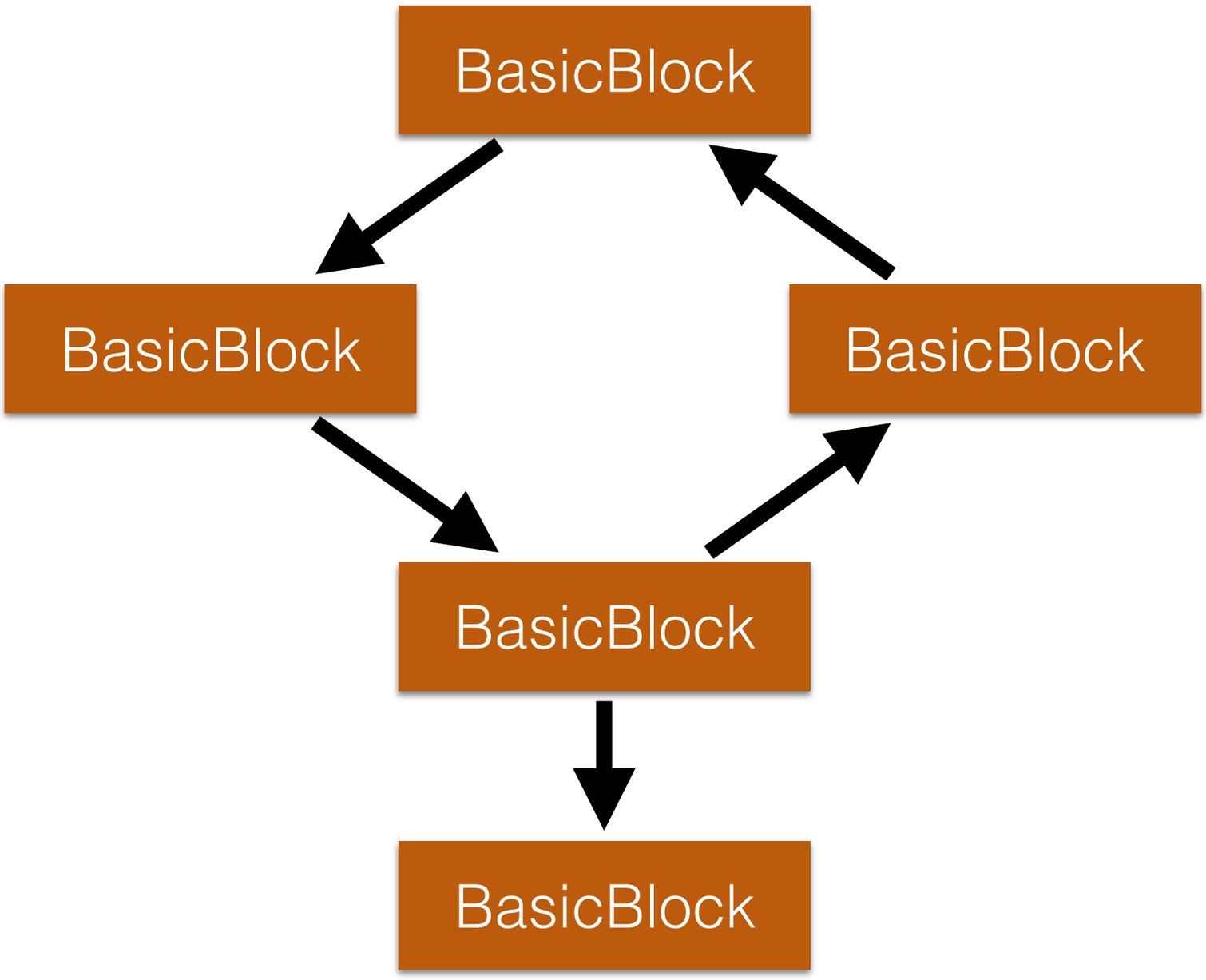
Push successor blocks to work list

exercise 7.1

What’s wrong in this implementation?

Loops!

Loops of Basic Blocks



Parameter Data-Flow Analysis

flow-sensitive version

Strategies for Handling Loops

- Only visit a BasicBlock once
- Only visit with different input flow
- Only push to worklist, if output set was not seen before

exercise 7.2

flow-sensitive version

Parameter Data-Flow Analysis

Strategies for Handling Loops
1. Process Blocks Once

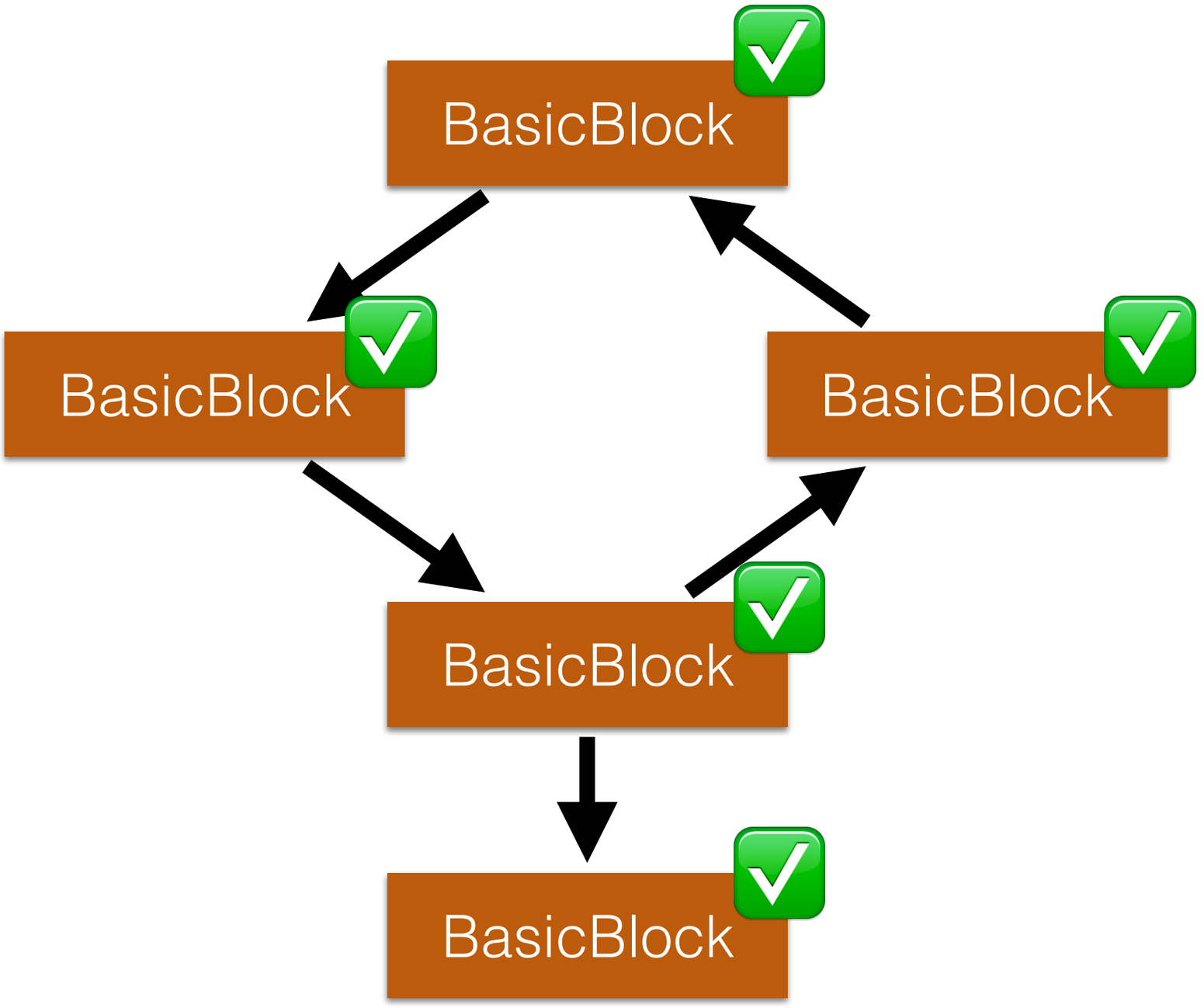
```
DenseSet<BasicBlock*> processed;

// compute outgoing values
processed.insert(current.first);

if (processed.find(succ) == processed.end())
   // add to worklist
```


exercise 7.2a

Strategy #1



exercise 7.2a

Parameter Data-Flow Analysis

flow-sensitive version

Strategies for Handling Loops
2. Consider Input Flows

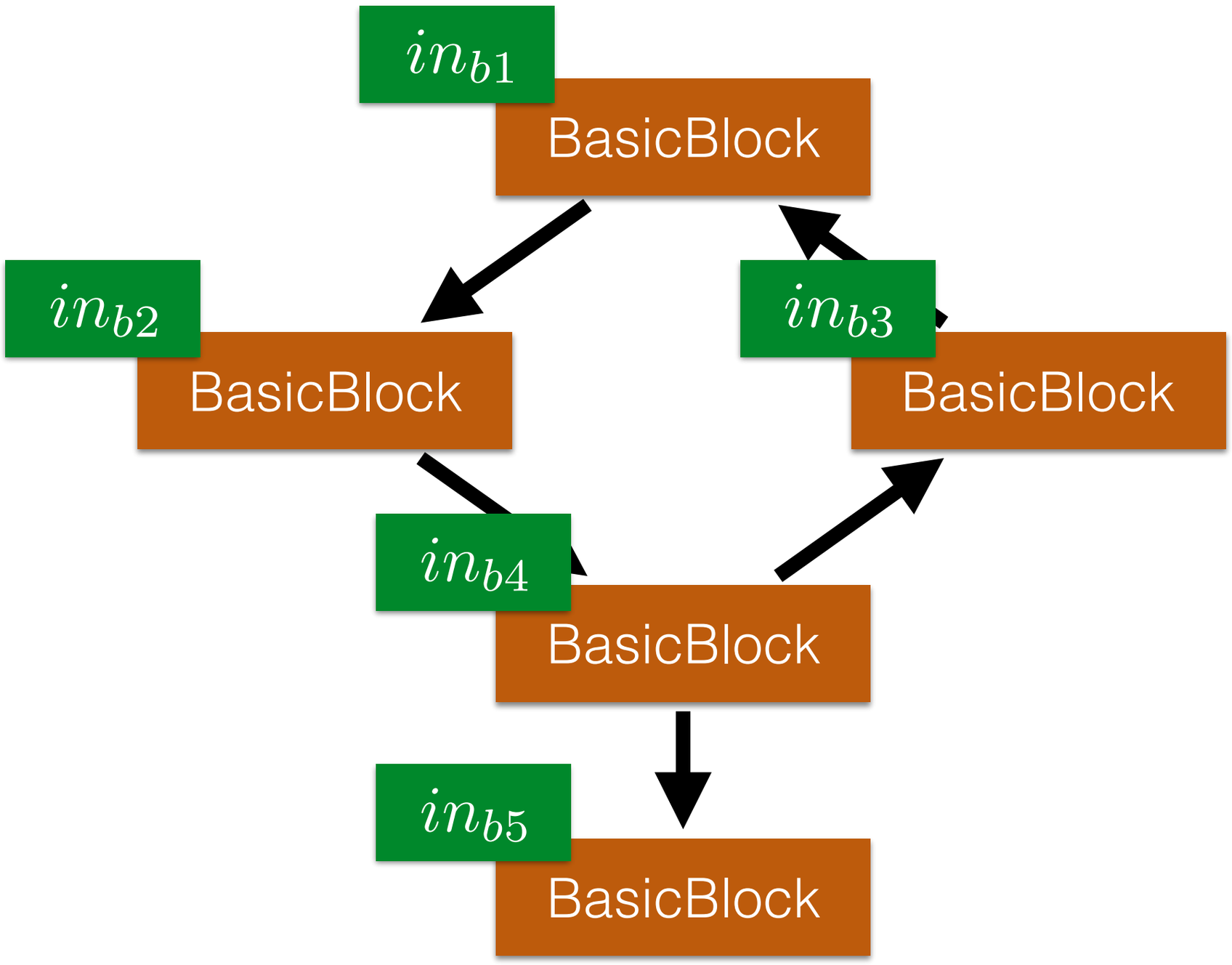
```
DenseMap<BasicBlock*, DenseSet<Value*>> knownInputs;
```

```
DenseSet<Value*> processedBeforeWith = knownInputs.lookup(current.first);
if (processedBeforeWith.size() > 0 &&
    valueSetsAreEqual(current.second, processedBeforeWith))
        continue;

if(knownInputs.count(current.first) == 1) knownInputs.erase(current.first);
knownInputs.insert(std::make_pair(current.first, current.second);
```

exercise 7.2b

Strategy #2



exercise 7.2b

Parameter Data-Flow Analysis

flow-sensitive version

Strategies for Handling Loops
3. Consider Output Flows

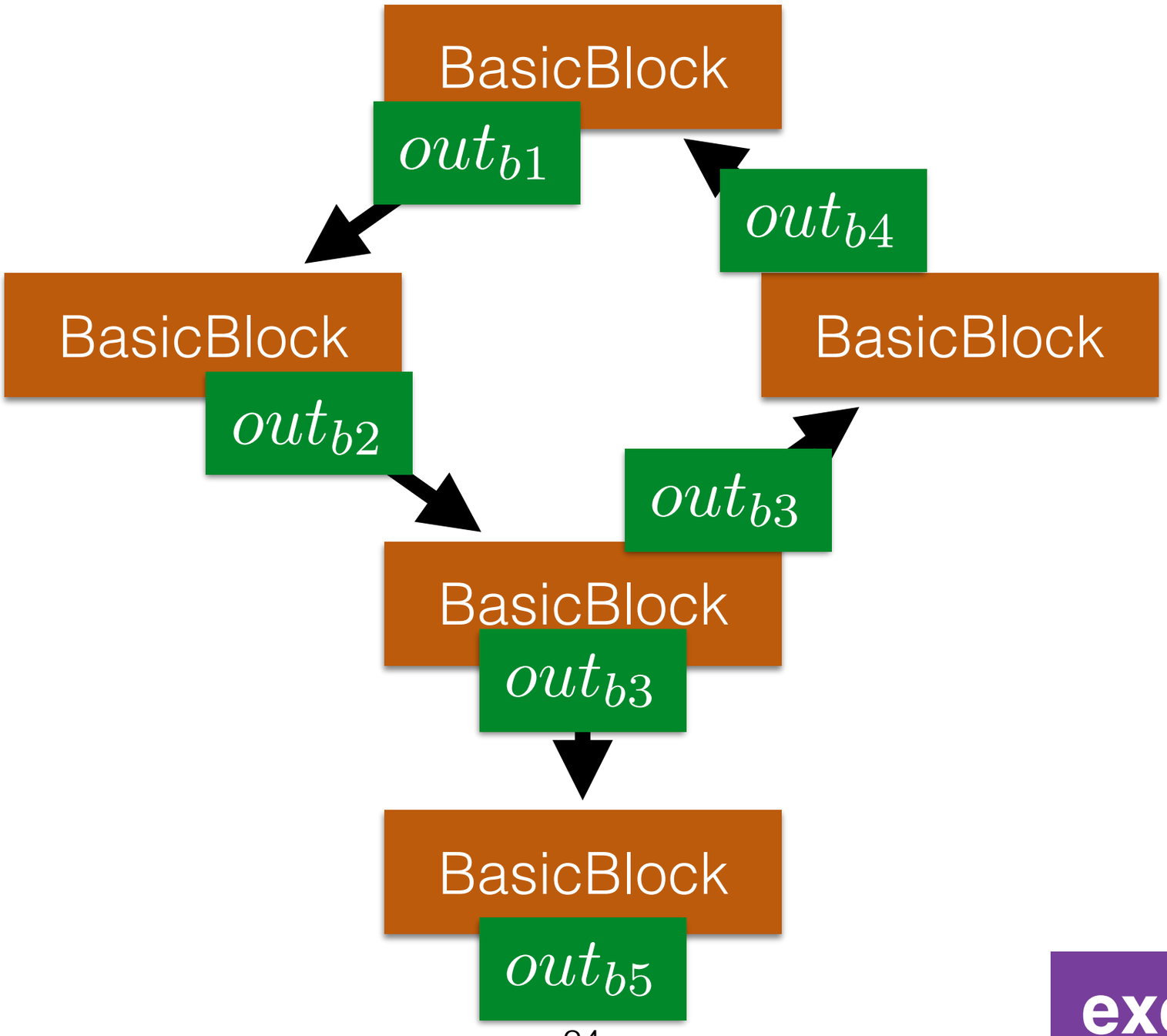
```
DenseMap<BasicBlock*, DenseSet<Value*>> previousOutputs;
```

```
if (previousOutputs.count(current.first) > 0) {
  DenseSet<Value*> previousOutput = previousOutputs.lookup(current.first);
  if (previousOutput.size() > 0 &&
      valueSetsAreEqual(outgoingTracked, previousOutput))
        continue;
  previousOutputs.erase(current.first);
}

previousOutputs.insert(std::make_pair(current.first, outgoingTracked));
```


exercise 7.2c

Strategy #3



exercise 7.2c

What's left to do?

- **Path-sensitivity** — Reconstruct conditions
- **Context-sensitivity** — Implement more clever call handling

- This exercise is just for your own curiosity, I won't present a solution in the next lecture

exercise 7.3

Writing Transformers

Why transform code?

- Finding problems in code is nice
- Solving them automatically is much, much nicer
- Can be part of your usual compile pipeline and helps you maintain quality
- Make runtime observations w/o cluttering your code

How to Write a Transformer?

`exercises/FirstTransform/`

- A transformer is a normal pass
- But it returns **`true`** to signal code changes

```
for(BasicBlock &bb : F) {
   Instruction *firstInst = bb.getFirstNonPHI()
   IRBuilder<> builder(firstInst);
   Instruction *newInst =
       builder.CreateAlloca(Type::getInt32Ty(bb.getContext()));
}
```

Get the first instructions

Construct a IRBuilder

Create an **`alloc`** instruction

exercise 7.4

Running a Transformer

- Much like an analysis pass

```
opt-3.8 -load FirstTransform/libFirstTransform.so
        -FirstTransform
        < factorial.bc
        > factorial-transformed.bc
```

```
opt-3.8 -load FirstTransform/libFirstTransform.so
        -FirstTransform
        --debug-pass=Structure
        < factorial.bc
        > /dev/null
```

Show me the structure of the pipeline

exercise 7.4

Pass Structure

```
Pass Arguments:  -targetlibinfo -tti -FirstTransform -verify
Target Library Information
Target Transform Information
  ModulePass Manager
    FunctionPass Manager
      First transform
      Module Verifier
    Bitcode Writer
```

Pass managers try to optimize the execution of passes

Verifies the resulting bitcode

Emits bitcode

PassManager

- Its job:
  - Pipeline the execution of passes on the program
    - Share the results of analyses
- There is no need for you to call it directly
- However, you can help the `PassManager`

PassManager

- Help the `PassManager` do its job

```
virtual void getAnalysisUsage(AnalysisUsage &Info) const;
```

```
// This example modifies the program, but does not modify the CFG
void LICM::getAnalysisUsage(AnalysisUsage &AU) const {
  AU.setPreservesCFG();
  AU.addRequired<LoopInfoWrapperPass>();
}
```

Provide information on your pass

Require other passes

PassManager

- Get modularity in return

```
bool runOnFunction(Function &F) override {
  LoopInfo &LI = getAnalysis<LoopInfoWrapperPass>().getLoopInfo();
  //...
}
```

Get a reference to the required other pass

Retrieve information from other pass

```
if (DominatorSet *DS = getAnalysisIfAvailable<DominatorSet>()) {
  // A DominatorSet is active.  This code will update it.
}
```

General Structure of a Transformer

Identify

Your job

Inject

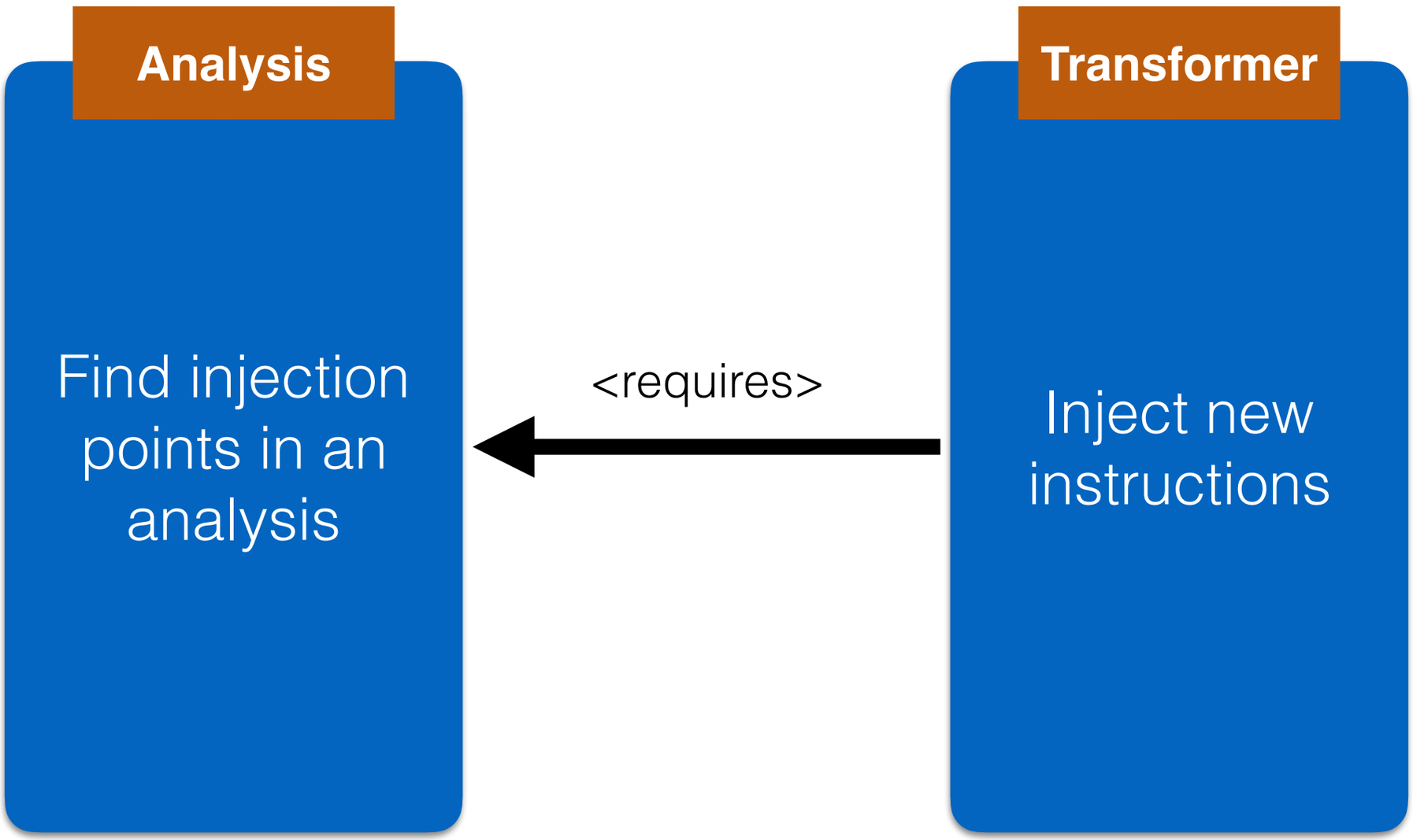
Your job

Emit

LLVM takes care of that

Chain you Passes

just a matter of style



Exercise: Observe pointer instructions during runtime

- Pointer operations can lead to serious issues during runtime
- Moving a pointer to a different region of memory can lead unexpected results
- Reasoning about pointers statically is pretty hard
- Goal: Observe pointer instructions during runtime

exercise 7.5

Identification Phase

```
DenseSet<Instruction*> pointerInstructions;
for(BasicBlock &bb : f) {
    for(Instruction &i : bb) {
        if (GetElementPtrInst* gep = dyn_cast<GetElementPtrInst>(&i)) {
          pointerInstructions.insert(gep);
        }
    }
}
```


exercise 7.5

Injection Phase

```
for (Instruction *i : pointerInstructions) {
  errs() << "Injecting print operation\n";
  IRBuilder<> builder(i);
  Function *printfFunction = getPrintFPrototype(i->getContext(),
                                                i->getModule());

  builder.CreateCall(printfFunction,
                     geti8StrVal(*i->getModule(),
                                 "Pointer instruction\n",
                                 "name"));
}
```

exercise 7.5

Function Prototypes

```
Function *getPrintFPrototype(LLVMContext &ctx, Module *mod) {
  FunctionType *printf_type =
      TypeBuilder<int(char*, ...), false>::get(getGlobalContext());
  Function *func = cast<Function>(
           mod->getOrInsertFunction("printf", printf_type,
           AttributeSet().addAttribute(mod->getContext(), 1U,
           Attribute::NoAlias)));
  return func;
}
```


exercise 7.5

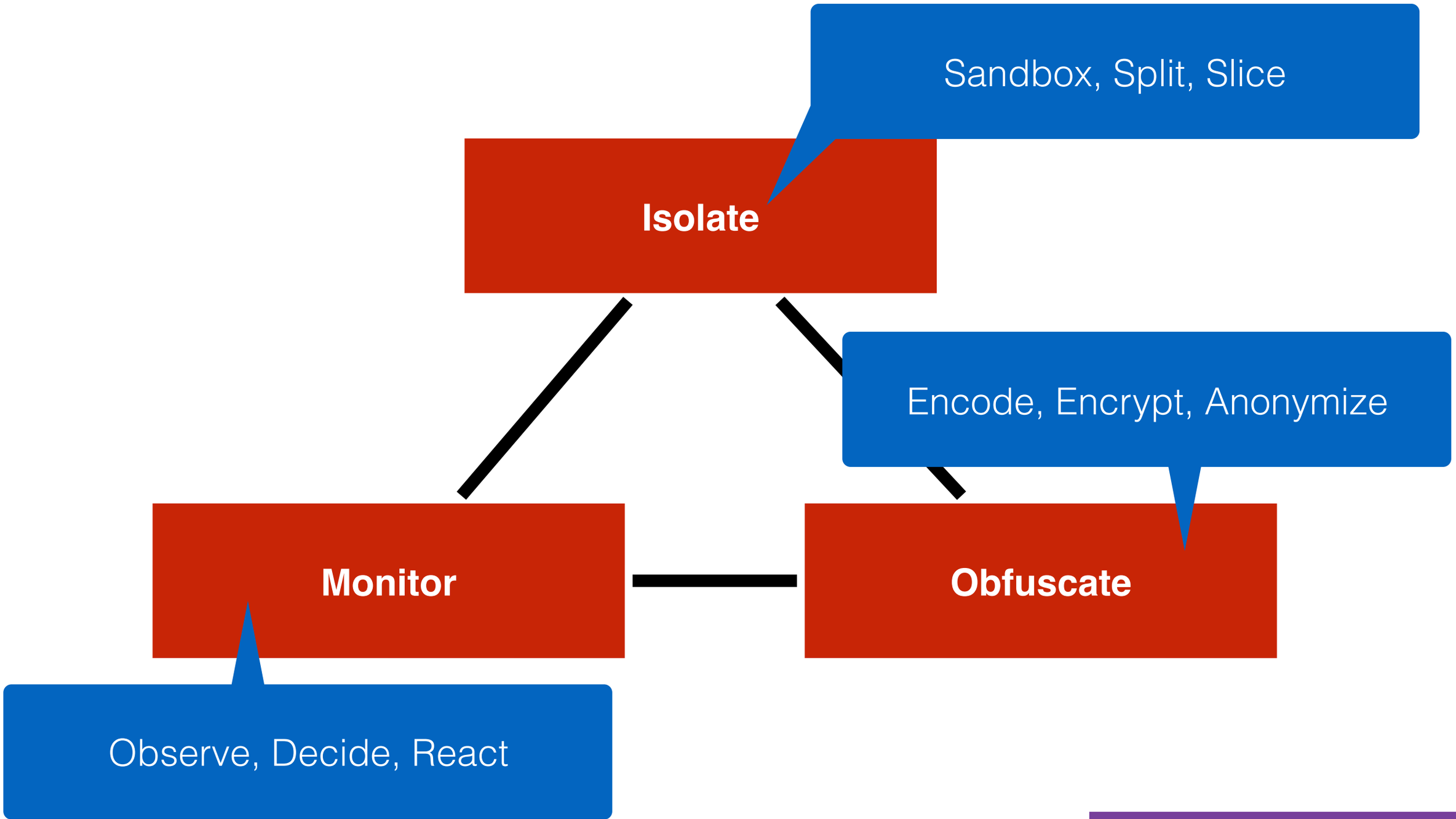
String Constant

```
Constant* geti8StrVal(Module& M, char const* str, Twine const& name) {
  LLVMContext& ctx = getGlobalContext();
  Constant* strConstant = ConstantDataArray::getString(ctx, str);
  GlobalVariable* GVStr =
      new GlobalVariable(M, strConstant->getType(), true,
                         GlobalValue::InternalLinkage, strConstant,
                         name);
  Constant* zero = Constant::getNullValue(IntegerType::getInt32Ty(ctx));
  Constant* indices[] = {zero, zero};
  Constant* strVal = ConstantExpr::getGetElementPtr(Type::getInt8PtrTy(ctx),
                                                    GVStr, indices, true);
  return strVal;
}
```

There is an error here… Can you provide the correct type?

exercise 7.5

Dimensions of Security



exercise 7.6

Exercise: Inline Reference Monitor

- A reference monitor observes the execution of a program

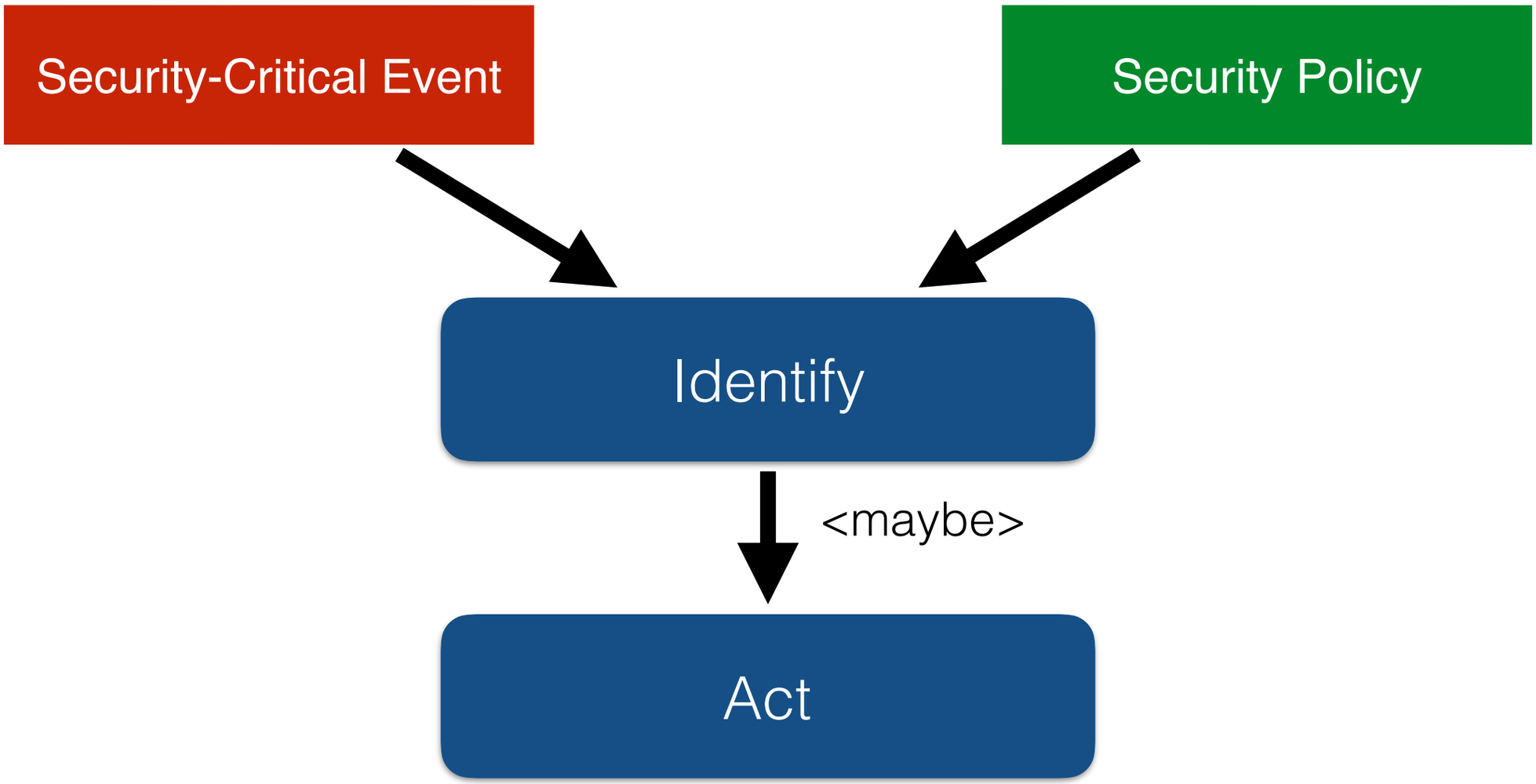
- It halt or pauses the execution if something “bad” happens

- What “bad” ist defines a security policy

- It makes sense to observe only security critical events

exercise 7.6

Exercise: Inline Reference Monitor



exercise 7.6

Exercise: Inline Reference Monitor

- Goal: Write a transformer that injects a reference monitor according to the following specification.

Security-Critical Event	Any function calls
Security Policy	Prevent function calls when the first argument is a number of value 42

- If you want to make that very elegant you decompose it into different passes and make it configurable

exercise 7.6

Shameless Advertisement

- Yes, I do some of my research using LLVM
- There are topics for Master Theses
- There are topics for Hands-On Courses
- It’s all security related
- Please talk to me if you liked the things we did here

Exercises in this Block

exercise 6.6	Parameter Data-Flow Analysis	
exercise 7.1	Control-Flow Sensitivity	
exercise 7.2	Handling Loops	
exercise 7.3	Path- & Context-Sensitivity	
exercise 7.4	Writing Transformers	
exercise 7.5	Observe Pointer Operations	
exercise 7.6	Inline Reference Monitor	

IFDS-Exercise Set-Up

Compiling OPAL may take some time, therefore start with the set up now, if not already done.

git clone https://bitbucket.org/delors/opal.git
git clone https://github.com/Sable/heros.git
git clone https://github.com/stg-tud/apsa.git
cd opal
git checkout develop
sbt publishLocal
cd ../heros
cp ant.settings.template ant.settings
mkdir javadoc
ant publish-Local
cd ../apsa/2016/ifds/ifds-exercise
sbt eclipse

From within Eclipse select Run As → Ant Build… on the build.xml file

Import projects IFDS-exercise and IFDS-testcases in Eclipse
Verify set-up: should compile without errors, some tests should succeed