IDFFL: An Intraprocedural Data Flow Framework for LLVM

Project Report Presentation By:
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Sections:

- A brief Intro to LLVM
- Introduction to Data Flow Analysis
- Foundation Theory for Framework
- Implementation of Framework for LLVM
- Possible future work

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Compiler Infrastructure, open source

Tools, analysis passes, transformation passes and some subprojects

Being used in compiler related research a lot now

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high level language		in LLVM IR		Target dependent
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- Can represent high level language constructs
- Defined with well-defined semantics
- Three forms bitcode, human-readable, and in-memory

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```
clang -S -emit-llvm hello.c     <-----     gives a .ll file
clang -c -emit-llvm hello.c     <-----     gives a .bc file
```

A brief Intro to LLVM(cont...)

bitcode(*.bc)
Efficient format for storage
Backward compatibility

llvm-dis →

← llvm-as

human readable(*.ll)

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- SSA form

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IR Layout

Module : a translation unit or many merged together

- consists Target info, global variables, function declarations, function definitions , and other stuff.

Function :

- consists a list of arguments, an entry Basic block, and more Basic blocks

Basic Block :

- consists a label, some phi instructions, some other instructions, a terminator instruction

A brief Intro to LLVM(cont...)

```
int factorial(int val);

int main(int argc, char** argv){
	return factorial(2) * 7 == 42;
}
```

LLVM IR

```
declare i32 @factorial(i32)

define i32 @main(i32 %argc, i8** %argv){
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	%2 = mul i32 %1, 7
	%3 = icmp eq i32 %2, 42
	%res = zext i1 %3 to i32
	ret i32 %res
}
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infinite registers

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some types are

- void type, function type, integer type, floating point type, pointer type, array type, structure type, etc.

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declaration of function

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phi inst : phi function in SSA form

- select value based on the bb that executed previously
- -O1 compiled IR usually have phi inst
- -O0 compiled IR has load and store insts, usually do not have phi insts

Introduction to Data Flow Analysis

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- Global Analysis - in a Control flow graph of a Function
- Interprocedural DFA - across functions (not implemented yet)

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- flow values associated with each PP shows the states possible

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Transfer function : to define relationship between program points before and after stmt

- can be defined for basic blocks

Merge operation : to combine information from predecessor blocks or successors blocks

- for forward analysis : combine predecessor info
- for backward analysis : combine successor info

Local information of basic block : generated by BB and destroyed by BB

- used in transfer functions

Introduction to Data Flow Analysis(Cont...)

Equations for forward analysis:

$$OUT[b] = f_b(IN[b])$$

$$IN[b] = \oplus_{p \in PRED(b)} OUT[p]$$

Where,

IN[b] is incoming info for basic block b

OUT[b] is outgoing info for basic block b

f_b is transfer function for basic block b

$\oplus$ is merge operation

PRED(b) is a list of predecessor of b

For backward analysis,

- exchange IN and OUT and replace predecessor list by successor list

f_b uses kill and gen local information and equation becomes

$$OUT[b] = IN[b] - kill[b] \cup gen[b]$$

Foundation Theory for Framework

A unified framework to defined the core concepts, to give answers for correctness, precision, convergence and speed of convergence for many similar problems and to reuse code.

Framework has four elements (V, $\wedge$, F, D):

V is the domain of values
$\wedge$ is the meet operator, a binary relation, with reflexivity, antisymmetry, and transitivity
F is a set of flow functions
D is the direction of the flow

(V,$\wedge$) define a semi-lattice with a top element $\top$ and an optional bottom element $\perp$.

- $x,y \in V$ are ordered : $x \leq y$ then $x \wedge y = x$
- The lattice is finite. Height = max # $\leq$ relations
- called finite descending chain

F has identity function $I(x) = x$, is closed under composition and are monotone and distributive.

Foundation Theory for Framework(cont...)

The iterative algorithm resemble the fixed point algorithm

```
x = ⊤;
while(x != f(x))
        x = f(x);
return x;
```

Fixed point algorithm
Where,
f is a monotone function defined on a semilattice

```
In{Exit} = BI
for (every other block B)
        In[B] = ⊤
change = 1
while (change)
        change = 0
        for (every basic block b)
                Out_b = ⊓_{s∈succ(n)} In_b
                tmp_b = f_p(Out_b)
                if tmp_b and In_b not same
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Iterative algorithm for data flow analysis

- Ideal Solution : solution of all executable paths(undecidable)
- Meet over paths: MOP(n) = f_{pi}(T), for all paths p_i reaching n (MOP)
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$$MFP \leq MOP \leq IDEAL$$

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We use C++ templates and LLVM as backbone in our framework

We define mostly all classes as templates

- user can defined own properties

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BoundedSet<>

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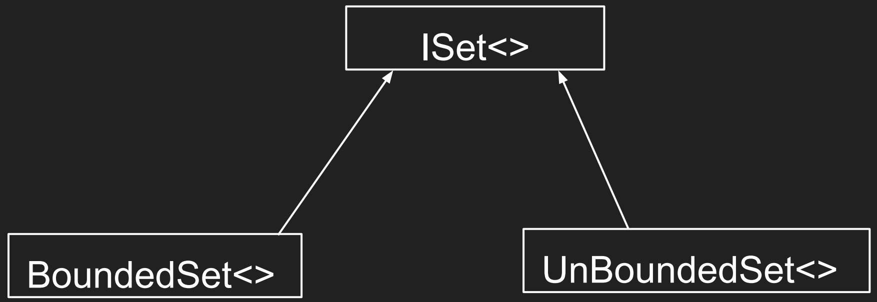
- ISet<> works as a interface class



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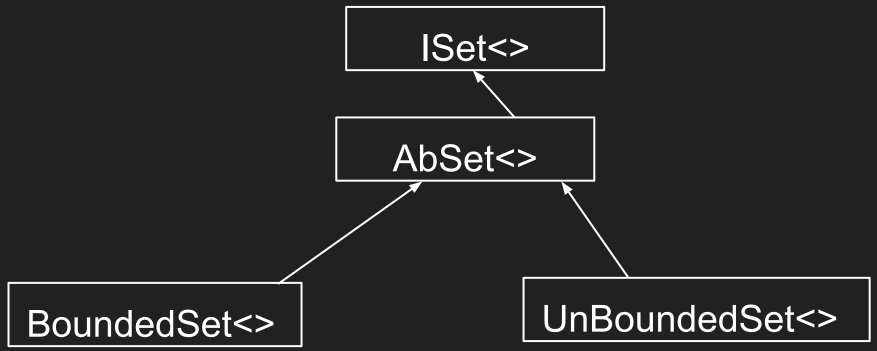

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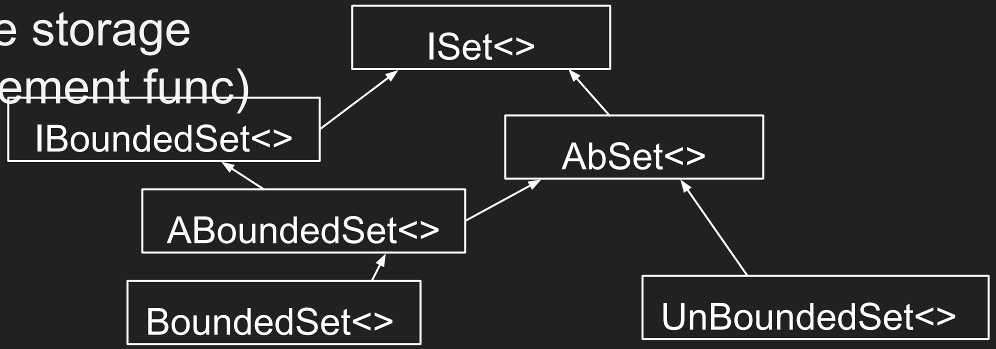
    - One more level(topset and complement func)
    - Uses a bidirectional map and Bitvector



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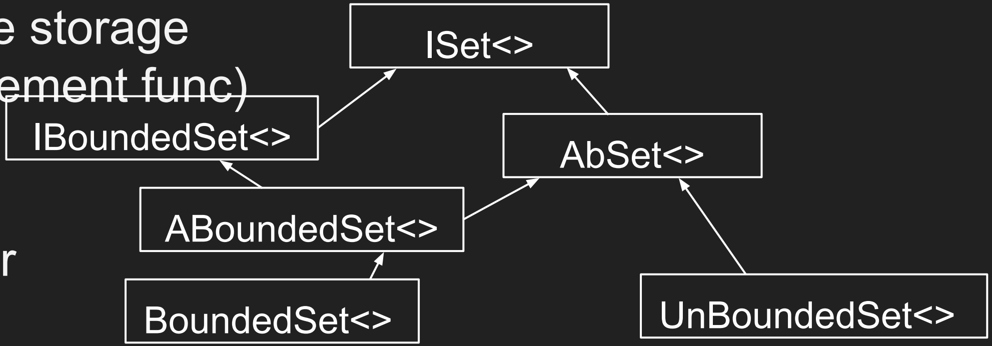
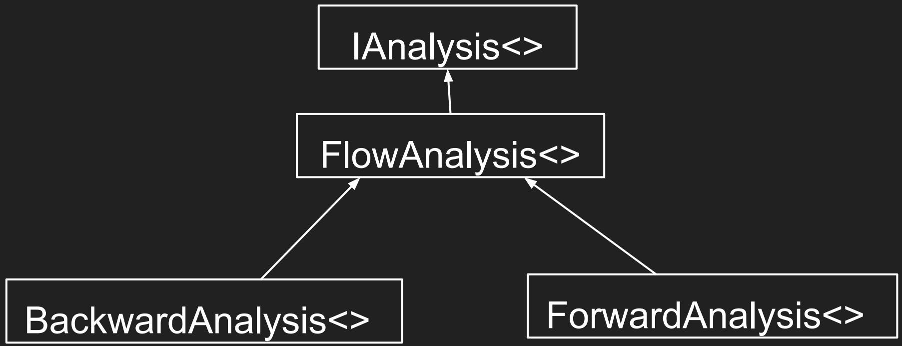
- UnBoundedSet<> uses a set container



Implementation of Framework for LLVM(cont..)

Analysis section :

- IAnalysis<> provides functions that user defines
  - NewInitialFlowSet, EntryInitialFlowSet, Merge, Copy, FlowThrough
- User inherits either of BackwardAnalysis<> or ForwardAnalysis<>



Implementation of Framework for LLVM(cont..)

Analysis section :

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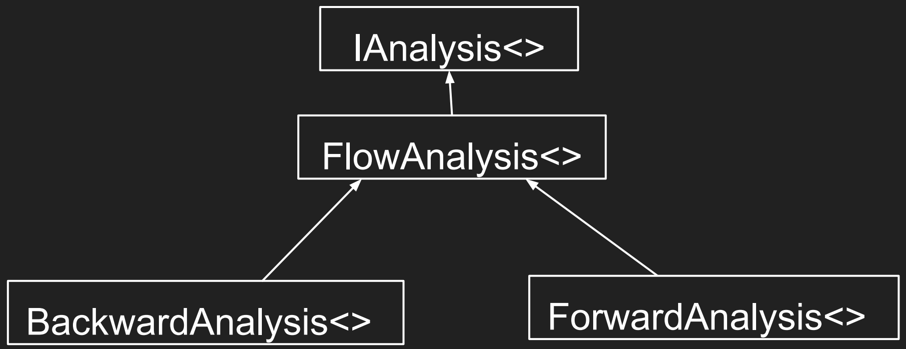
  - NewInitialFlowSet, EntryInitialFlowSet, Merge, Copy, FlowThrough
- User inherits either of BackwardAnalysis<> or ForwardAnalysis<>
- FlowAnalysis<> does the work
  - Creates a FunctionCFG (LLVM does not provide a CFG object)
  - Creates a NodeData<> object for each CFG node
  - NodeData<> class stores results and pointers to NodeData<> objects of the predecessor nodes and successor nodes
  - Adds the NodeData<> objects in a vector in post order or reverse post order
  - Uses this vector in iterative algorithm



Usage details

We give some macros to use framework easily.

Define analysis in either

FORWARDANALYSIS(...){...} or BACKWARDANALYSIS(...){...}

- Pass three args 1. name for analysis, 2. Storage class name, 3. user-defined property class
- User defines a class for property and a function definition in EXTRACT(){...}
    - Outside the analysis
- Inside analysis
    - function setup with SETUP_FUNCTION()
    - Call DoAnalysis()
    - Use BS_INITIALVALUE(), BS_ENTRYVALUE(), BS_MERGE(), BS_COPY(), and BS_FLOWTH() to give various framework definition
        - For UnBoundedSet use UBS_*
    - In *_FLOWTH() give definition for Gen and Kill also and call AddGenKill(...) on them and use GetGen() and GetKill().

Usage details

```
// define a property class here
EXTRACT(property_class_name){ // definition for extracting properties
  ...
}
BACKWARDANALYSIS(analysis_name,storage_class_name,property_class_name){
  static char ID; // used by LLVM internals
  string funcName; // store function name for analysis
  storage_class_name<property_class_name> *domain; // store properties

  analysis_name(string f): funcName(f),FunctionPass(ID){} // constructor

  RUN(){ // run the analysis
    SETUP_FUNCTION(); // function setup call
    domain = new storage_class_name<property_class_name>(&F); // extracting properties and assign
    DoAnalysis(); // start the analysis
    return false;
  }
  BS_INITIALVALUE(){ return domain->EmptySet();} // setting initial value to emptyset
  BS_ENTRYVALUE(){ return domain->EmptySet();} // setting entry value to emptyset
  BS_MERGE(property_class_name){ in1->Union(in2,out);} // setting meet operator to union
  BS_COPY(property_class_name){ in1->Copy(in2);} // providing copy definition
  BS_FLOWTH(property_class_name){ // definition for flow function
    // define kill
    // define gen

    storage_class_name<property_class_name>* tmp = domain->EmptySet();
    in->Difference(kill,tmp);
    tmp->Union(gen,out);
  }
};
```

Possible future work

- Add graphical interface
- Make even easier to use but still providing a general framework
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