Value Set Analysis in LLVM

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Value Set Analysis

Bounded Set Analysis:

$$Var \rightarrow \{a, b, c, ...\}_n$$

Interval Analysis:

$$Var \rightarrow [a : b]_n$$

Strided Interval Analysis:

$$Var \rightarrow s[a : b]_n$$

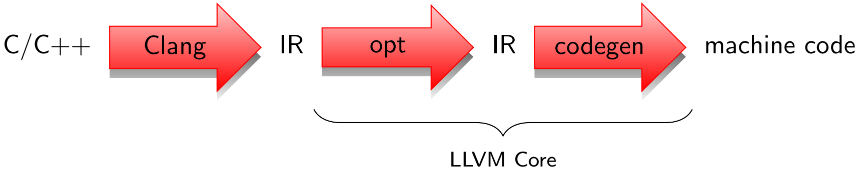
SSA $\Rightarrow$ sufficient to store the abstract value for each variable once per basic block:[1]

$$\mathcal{D} : BB \rightarrow Var \rightarrow Val$$

[1] The need to store it not just once only arises to preserve information at conditional branches.

Passes in LLVM

LLVM's analysis and optimization framework opt:



using existing passes (from command line):

```
opt -load -mem2reg -o hello-opt.bc < hello.bc
```

running user passes:

```
opt -load llvm/lib/llvm-vsa.so -vsapass -o hello.bc < hello.bc
```

Passes in LLVM (cont.)

Creating user passes:

- inherit from existing passes (module, function, block):

```
struct ThisPass : public ModulePass {}
```

- specify required passes, which have to be run in advance:

```
void ThisPass::getAnalysisUsage(AnalysisUsage &AU) override {
  AU.setPreservesAll();
  AU.addRequired<OtherPass>();
}
```

- perform analysis by using/accessing results of other passes:

```
bool ThisPass::runOnModule(Module &M) override {
  auto& other_result =
    getAnalysis<OtherPass>(function).getResult();
  /* ... perform analysis and fill result ... */

  // Return if the pass modified the bitcode (no)
  return false;
}
```

- make results available for other pass (optional):

```
ThisResult& ThisPass::getResult(){ return result; }
```

Example

```
int main(int argc, char const *argv[]) {
    unsigned a = 0, b = 12, c = rand();

    while (a < b) { a+=4; b-=2; }

    if(a>6 && b<6){
        switch (a) {
            case  6: b = 99;  break;                        // reachable?
            case 12:
            case 13: b = a*2; break;
            default:
                c = c%18;
        }
    } else {
        a = 88;
    }

    printf("%d\n", a);          // what will/might be printed out?
    printf("%d\n", b);
    printf("%d\n", c);
}
```

LLVM's Intermediate Representation IR

```
define dso_local i32 @main(i31 %argc, i8** %argv) #0 {
entry:
   br label %while.cond

while.cond:
   %a.0 = phi i32 [  0, %entry ], [ %add, %while.body ]
   %b.0 = phi i32 [ 12, %entry ], [ %sub, %while.body ]
   %cmp = icmp ult i32 %a.0, %b.0
   br i1 %cmp, label %while.body, label %while.end

while.body:
   %add = add i32 %a.0, 4
   %sub = sub i32 %b.0, 2
   br label %while.cond

while.end:
   %call = call i32 @rand() #3
   %cmp1 = icmp ugt i32 %a.0, 6
   br i1 %cmp1, label %land.lhs.true, label %if.else

land.lhs.true:
   %cmp2 = icmp ult i32 %b.0, 6
   br i1 %cmp2, label %if.then, label %if.else
```

... and many more lines of code

Content of the Lab

Tasks:

- implement abstract domains that suitably represent value sets
- develop a new analysis tool in LLVM to determine the value set of each variable, using visitor and fixpoint algorithm (worklist) ▷ VSAPass
- make results accessible via API: VSAResult and VSAResultValue
- compare results with LLVM's LazyValueInfo

Future work:

- widening and narrowing
- inter-procedural analysis
- memory access

unknowns (ops, return values and arguments of functions) treated as: $\top$

Part 1:

Abstract Domain

Background to LLVM Integer Types

- In LLVM the type of N-bit integers is the set $\mathtt{i}N \coloneqq \{0,1\}^N$, for $N \in \{1, \ldots, 2^{23} - 1\}$.
- "$\mathtt{i}N \cong \mathbb{Z}/2^N$"
- In the in-memory-representation, these types are represented by the LLVM class APInt.
- This type is used for both signed and unsigned integers.
- We use APInt in our implementation of abstract domains.

LLVM Integer Operations

Arithmetic Operations:

In LLVM there are separate `div` and `rem` operations for signed and unsigned integers. For `add`, `sub` and `mul`, there is no such distinction needed.

- `<result> = add [nuw] [nsw] <bitWidth> <op1> <op2>`
- `<result> = sub [nuw] [nsw] <bitWidth> <op1> <op2>`
- `<result> = mul [nuw] [nsw] <bitWidth> <op1> <op2>`
- `<result> = udiv [exact] <bitWidth> <op1> <op2>` [2]
- `<result> = sdiv [exact] <bitWidth> <op1> <op2>` [2]
- `<result> = urem <bitWidth> <op1> <op2>`
- `<result> = srem <bitWidth> <op1> <op2>`

`nuw` : "no unsigned wrap", `nsw` : "no signed wrap"

[2] exact-flag not used in our implementation.

LLVM Integer Operations (cont.)

Bitwise Operations:

- `<result> = shl [nuw] [nsw] <bitWidth> <op1> <op2>`
- `<result> = lshr [exact] <bitWidth> <op1> <op2>` [3]
- `<result> = ashr [exact] <bitWidth> <op1> <op2>` [3]
- `<result> = and <bitWidth> <op1> <op2>`
- `<result> = or <bitWidth> <op1> <op2>`
- `<result> = xor <bitWidth> <op1> <op2>`

[3] exact-flag not used in our implementation.

Bounded Set

- A bounded set represents a set of values up to a given cardinality k, or $\top$: $\mathrm{BS}_N := \{M \in \mathcal{P}(\mathtt{i}N) \mid |M| \leq k\} \dot{\cup} \{\top\}$
- $\sqcup$ and $\sqsubseteq$ on bounded sets essentially reduce to $\cup$ and $\subseteq$ on sets.
- Any set with more elements than k is over-approximated by $\top$.
- $\gamma_{BS_N} : \mathrm{BS}_N \to \mathcal{P}(\mathtt{i}N), b \mapsto \begin{cases} \mathtt{i}N, & \text{if } b = \top \\ b, & \text{otherwise} \end{cases}$

Modular Strided Interval (MSI)

- Intervals:
  - $\mathsf{I} := [a, b]$, for $a, b \in \mathbb{Z}$
- Strided Intervals:
  - $\mathsf{SI} := s[a, b]$, for $a, b \in \mathbb{Z}, s \in \mathbb{N}$
  - $\gamma_{\mathsf{SI}} : \mathsf{SI}_N \to \mathcal{P}(\mathbb{Z}), s[a, b] \mapsto \{k \in \mathbb{Z} \mid a \leq k \leq b, k \equiv a \mod s\}$
- Modular Strided Intervals:
  - $\mathsf{MSI}_N := \{s[\overline{a}, \overline{b}]_N \mid \overline{a}, \overline{b} \in \mathbb{Z}/2^N, s \in \{0, \ldots, 2^N\}\} \,\dot{\cup}\, \{\perp\}$
  - $\gamma_{\mathsf{MSI}_N} : \mathsf{MSI}_N \to \mathcal{P}(\mathtt{i}N)$,

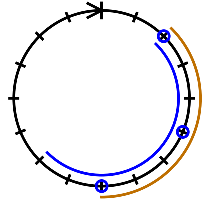
$$i \mapsto \begin{cases} \emptyset, & \text{if } i = \perp \\ \{k + 2^N\mathbb{Z} \mid k \in \mathbb{Z}, a \leq k \leq c, k \equiv a \mod s\}, & \text{if } i = s[\overline{a}, \overline{b}]_N \\ \quad \text{where } c = \min\{x \in \mathbb{Z} \mid x \geq a, & \\ \qquad x \equiv b \mod 2^N\} & \end{cases}$$

  - Examples:
    - $12[15, 63]_8 \xrightarrow{\gamma} \{15, 27, 39, 51, 63\} \subseteq \mathbb{Z}/2^8$
    - $4[10, 6]_4 \xrightarrow{\gamma} \{10, 14, 2, 6\} \subseteq \mathbb{Z}/2^4$

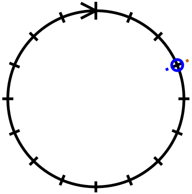
Modular Strided Interval: Normalization

Note that some sets can be represented by muliple MSIs. Thus, we introduce a predicate *normal*, such that there is at most one *normalized* representation.
Examples:

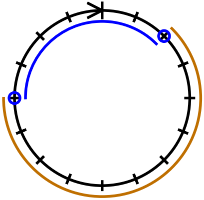
$3[2, 10]_4 \downarrow 3[2, 8]_4$



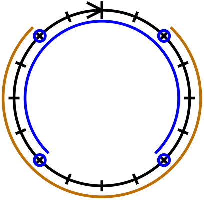
$4[3, 3]_4 \downarrow 0[3, 3]_4$



$6[12, 2]_4 \downarrow 10[2, 12]_4$



$4[10, 6]_4 \downarrow 4[2, 14]_4$



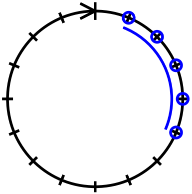
Modular Strided Interval: Normalization (cont.)

$$
\begin{aligned}
&\mathrm{normal}_N(s[\overline{a}, \overline{b}]_N) \leftrightarrow (\\
&\qquad \overline{a} = \overline{b} \to s = 0 \\
&\quad \wedge\ \overline{b} \in \gamma_N(s[\overline{a}, \overline{b}]_N) \\
&\quad \wedge\ \overline{a} = \min\{a' \in \{0 \ldots 2^N - 1\}.\ \exists s', \overline{b}'.\ \gamma_N(s'[\overline{a'}, \overline{b}']_N) = \gamma_N(s[\overline{a}, \overline{b}]_N)\} + 2^N\mathbb{Z} \\
&)
\end{aligned}
$$

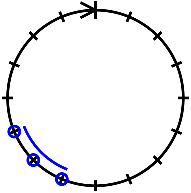
Modular Strided Interval: Union

MSIs do not form a lattice, as, in general, there is no *least* upper bound of two elements.
Example:

$1[1,5]_4$

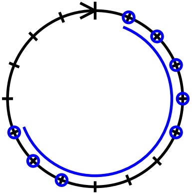


$\sqcup$ $1[9,12]_4$

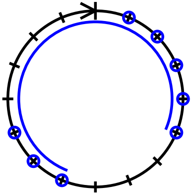


$=$

$1[1,12]_4$

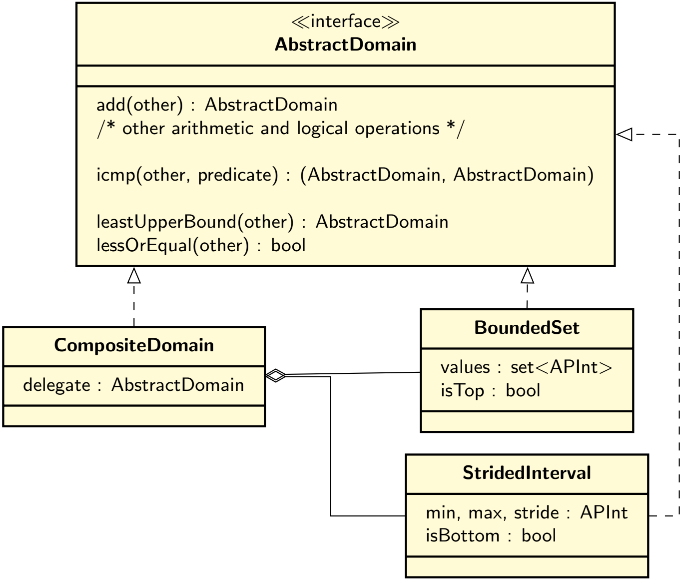


or $1[9,5]_4$



Therefore we try to find a *minimal* upper bound wrt. $|\gamma(\cdot)|$.

Abstract Domain Class Structure



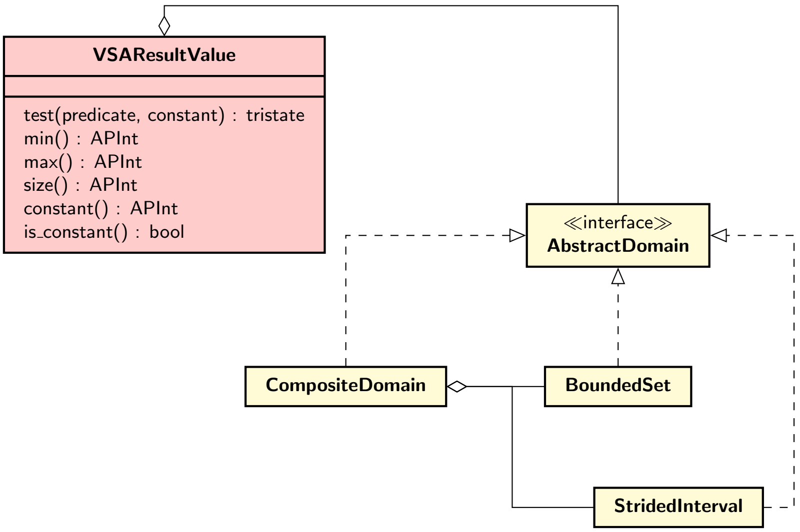
Application Interface

VSAResult
is_reachable(basic_block) : bool is_resultat_available(bb, value) : bool get_abstract_value() : VSAResultValue

VSAResultValue
test(predicate, constant) : tristate min() : APInt max() : APInt size() : APInt constant() : APInt is_constant() : bool

- after a successful pass:
  `auto& res = vsap.get_result();`
- query information related to basic block (reachable or not) and/or variable (abstract value)

Connection of the Results to the Internal Abstract Domain



Part 2:

Fixpoint Algorithm & Visitor

Data Structures

Data structures maintained during the analysis:

- state of each basic block (goal):

red: abstract domain

$$\mathcal{D} \,:\, BB \to \underbrace{(Var \to Val)_{\perp}}_{state\ \mathcal{D}_{BB}}$$

- branch conditions:

$$\mathcal{C} \,:\, \underbrace{(BB \to XX)}_{edge} \to \underbrace{(Var \to Val)_{\perp}}_{\mathcal{C}_{BB \to XX}}$$

$\to$ effect of a guard:

$$\mathcal{D}_{XX} \leftarrow [\![BB \to XX]\!]\, \mathcal{D}_{BB} = \mathcal{D}_{BB} \oplus \mathcal{C}_{BB \to XX}$$

Fixpoint Algorithm: Worklist

We maintain a worklist $\mathcal{W}$ of basic blocks to be (re)evaluated.

Algorithm 1 Fixpoint algorithm

procedure $\textsc{Fixpoint}$(Function)
    $\mathcal{W}$.push(Function.front()) ▷ push entry basic block of function
    while $!\,\mathcal{W}.\mathit{empty}()$ **then**:
        visit $\mathcal{W}$.pop()

Fixpoint algorithm terminates iff $\mathcal{W}$ is empty: a fixpoint has been found.

Following initial and entry states are used (forward analysis):

$$\mathcal{D}_0 \,:\, BB \to \bot \quad \text{and} \quad \mathcal{D}_{entry} \,:\, BB \to (Arg_i \to \top)$$

Visitor: (Entering) Basic Block

Visiting a basic block is a two-step process:

1. setting up the (temporary) input state $\mathcal{N}_{BB}$ during entering
2. visiting all its instructions

Algorithm 2 Enter basic block BB

```
1: procedure VISIT(BB)
2:     N_BB = ⊔{D_XX ⊕ C_XX→BB | XX ∈ prev(BB) ∧ D_XX ≠ ⊥}
3:     for each instruction ∈ instructions(BB):
4:         visit instruction
```

$$\mathcal{N}_{BB} = \bigsqcup \{\mathcal{D}_{XX} \oplus \mathcal{C}_{XX\to BB} \mid XX \in \mathrm{prev}(BB) \wedge \mathcal{D}_{XX} \neq \bot\}$$

<u>Explicitly considered instructions</u>:

- terminators: (un)conditional jumps, switches
- PHI nodes
- binary expressions

Visitor: Leaving Basic Block at Terminator

check for change of the local state and save it in $\mathcal{D}$:

Algorithm 3 Visit terminator

procedure $\textsc{Visit}$(Terminator)
    if $\mathcal{N}_{BB} \sqsubseteq \mathcal{D}_{BB}$ **then**: ▷ red: delegated to abstract domain
        return ▷ state has not changed
    $\mathcal{D}_{BB} \leftarrow \mathcal{N}_{BB}$
    for each $XX \in \text{next}(BB)$:
        if reachable(BB, XX) **then**:
            $\mathcal{W}$.push(XX)

in the case of change ($\mathcal{N}_{BB} \not\sqsubseteq \mathcal{D}_{BB}$), push all reachable successors:

- unconditional branch: push all successors
- conditional branch/switch: check if $\exists(\# \to \bot) \in \mathcal{C}_{BB \to XX}$

Visitor: Conditional Branch

Algorithm 4 Visit conditional branch (terminator)

procedure $\textsc{Visit}(\textsc{jmp}\,(x \,\square\, y \,?\, XX \;:\; YY))$
    if isVar(x) **then**:
        $\mathcal{C}_{BB \to XX} \leftarrow \mathcal{C}_{BB \to XX} \oplus \left\{x \;\to\; \mathcal{N}_{BB}[x] \;\square^{\#}\, \mathcal{N}_{BB}[y]\right\}$
        $\mathcal{C}_{BB \to YY} \leftarrow \mathcal{C}_{BB \to YY} \oplus \left\{x \;\to\; \mathcal{N}_{BB}[x]\,!\square^{\#}\, \mathcal{N}_{BB}[y]\right\}$
    if isVar(y) **then**:
        ...
    $\textsc{VisitTerminator}()$

considered comparisons:

$$\square \in \{=, \neq, <, \leq, \geq, >\}$$

Visitor: Switch

Algorithm 5 Visit switch (terminator)

1: **procedure** $\textsc{Visit}(\textsc{switch}\,[x = a : XX][x = b : YY][x = c : YY][default : ZZ])$
2: $\quad \mathcal{C}_{BB \to XX} \leftarrow \{x \to \mathcal{N}_{BB}[x] =^{\#} a\}$
3: $\quad \mathcal{C}_{BB \to YY} \leftarrow \{x \to (\mathcal{N}_{BB}[x] =^{\#} b) \sqcup (\mathcal{N}_{BB}[x] =^{\#} c)\}$
4: $\quad \mathcal{C}_{BB \to ZZ} \leftarrow \{x \to \mathcal{N}_{BB}[x] \setminus \{a, b, c\}\}$
5: $\quad \textsc{VisitTerminator}()$

Visitor: Parallel Assignments at PHI Node

Algorithm 6 PHI node in basic block BB

1: **procedure** $\textsc{Phi}(x \leftarrow [YY\ : y]\,[ZZ\ : z])$
2: $\quad \mathcal{N}_{BB} \leftarrow \mathcal{N}_{BB} \oplus \{x \rightarrow (\mathcal{D}_{YY} \oplus C_{YY \rightarrow BB})\,[y] \sqcup (\mathcal{D}_{ZZ} \oplus C_{ZZ \rightarrow BB})\,[z]\}$

Visitor: Binary Expressions

Algorithm 7 Addition in basic block BB

1: **procedure** $\textsc{Binary}(x \leftarrow y \,\square\, z)$

2: $\quad \mathcal{N}_{BB} \leftarrow \mathcal{N}_{BB} \oplus \left\{x \rightarrow \mathcal{N}_{BB}[y] \,\square^{\#}\, \mathcal{N}_{BB}[z]\right\}$

considered binary instructions:

$$\square \in \{+,\, -,\, \times,\, /,\, \%,\, \ll,\, \gg\}$$

Visitor: Memory access and Not-implemented Operations

Data in memory is considered unknown.

Algorithm 8 Load in basic block BB

1: **procedure** $\textsc{Visit}(x \leftarrow \textsc{load}(...))$

2: $\quad \mathcal{N}_{BB} \leftarrow \mathcal{N}_{BB} \oplus \{x \to \top\}$

Not-implemented operations of form $x \leftarrow \#$ are treated implicitly in the same way.

Part 3:

Livedemo

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