SVF: Static Value-Flow Analysis in LLVM

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Outline

- Static Value-Flow
- SVF Overview
- SVF Internals
- Results and Client Applications

Static Value-Flow Analysis

Statically resolves both control and data dependence of a program.

- Does the information generated at program point *A* flow to another program point *B* along some execution paths?
- Is there an unsafe memory access that may trigger a bug?

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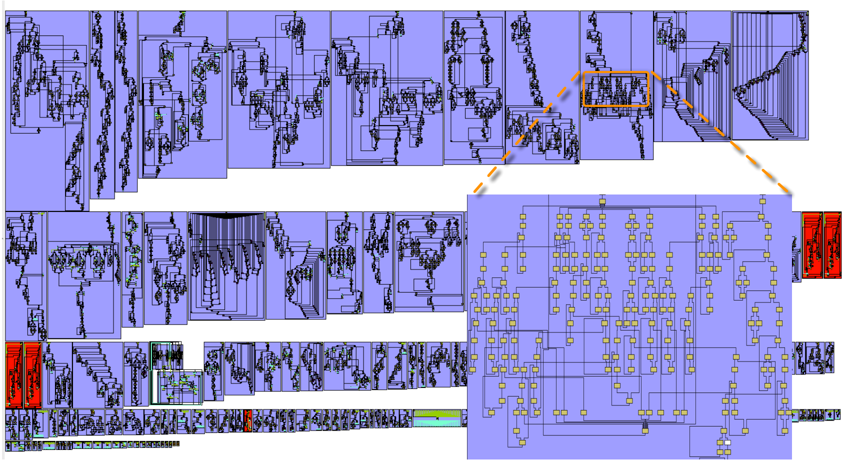
Value-flow (def-use) of a variable

- Def-use of a top-level pointer (register value) is explicit on LLVM SSA.
- Def-use of an address-taken variable (allocated memory objects) is hard to compute precisely and efficiently.

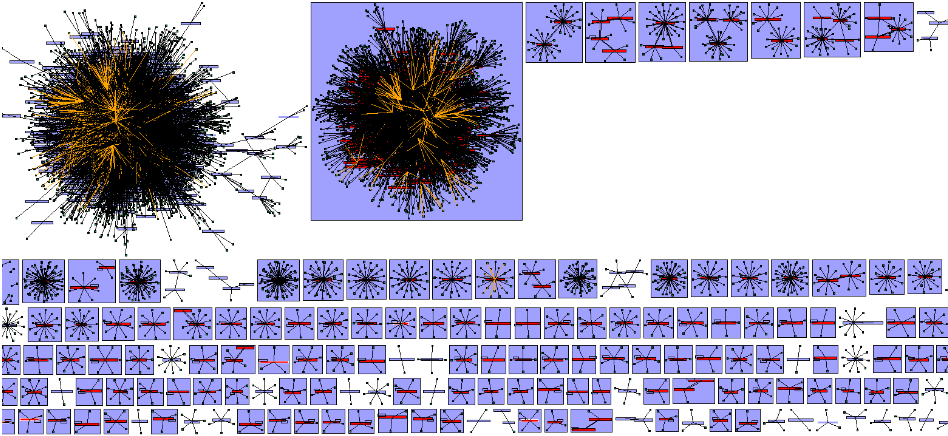
Whole-Program CFG of 300.twolf (20.5KLOC)



#functions: 194 #pointers: 20773 #loads/stores: 8657

Costly to reason about flow of values on CFGs!

Call Graph of 176.gcc



#functions: 2256 #pointers: 134380 #loads/stores: 51543

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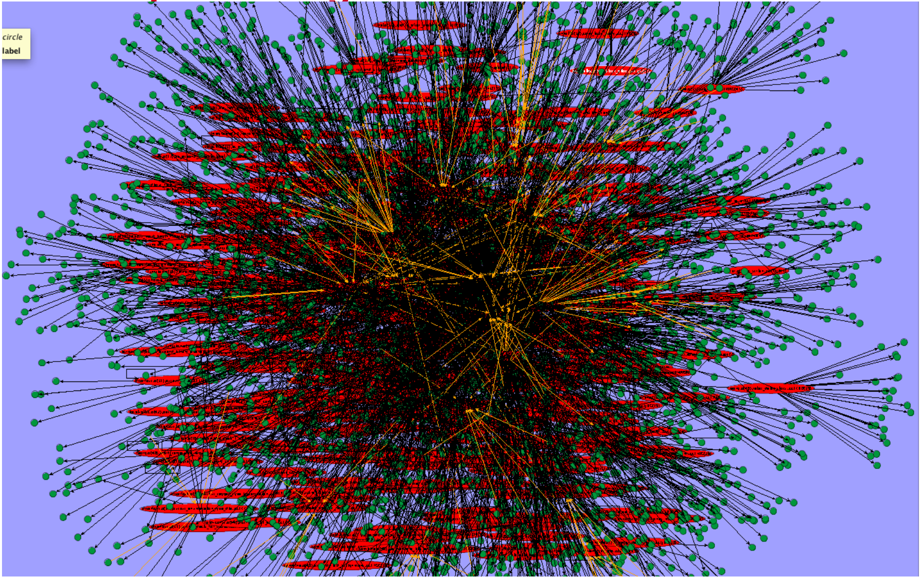

Motivation

Why need an interprocedural static value-flow analysis in LLVM?

- **Bridge the gap between research and engineering**
  - *Support developing different analysis variants (flow-, context-, heap-, field-sensitive analysis)*
  - *Minimize the efforts of implementing sophisticated analysis. (extendable, reusable, and robust via layers of abstractions)*

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  - *Static bug detection (e.g., memory leak, data-race)*
  - *Sanitizers (e.g., MSan, TSan)*
  - *Program understanding and debugging*

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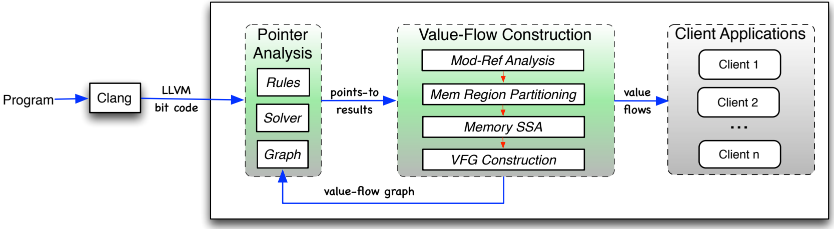
  - *Sanitizers (e.g., MSan, TSan)*
  - *Program understanding and debugging*
- **LLVM community support**
  - *Industrial-strength compiler with well-defined IR*
  - *Front-ends that support many different languages*
  - *Many active program analysis researchers and engineers*

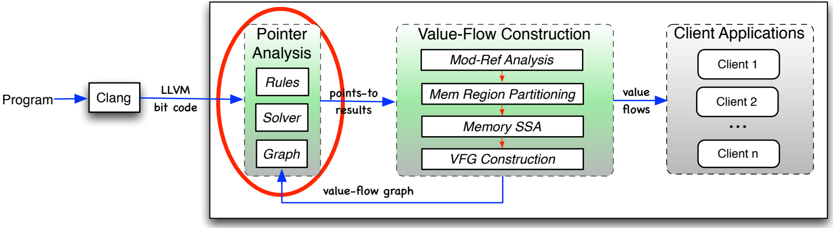
SVF Overview



A research tool supports refinement-based interprocedural program dependence analysis on top of LLVM.

- Pointer analysis and Value-flow construction are performed iteratively to provide increasingly improved precision for both.
- The project initially started from 2013 on LLVM-3.3. Now it supports LLVM-3.7.0 with around 50KLOC C++ code.
- Publicly available at: `http://unsw-corg.github.io/SVF/`

SVF Overview

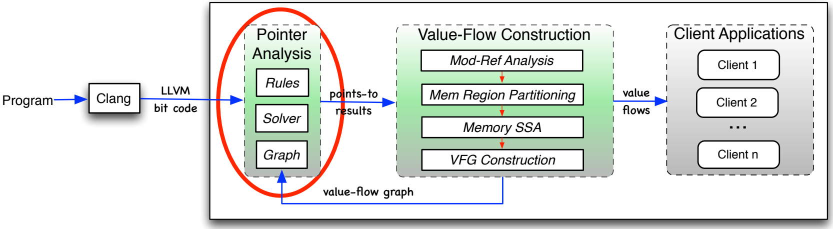


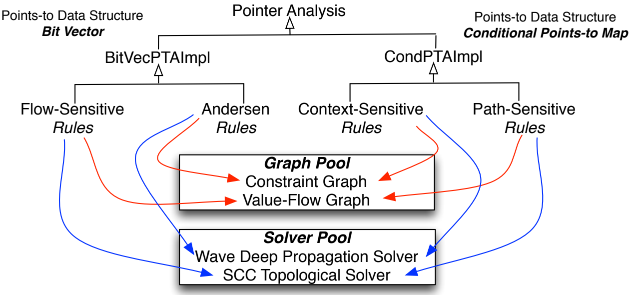
Support developing different analyses (flow-, context-, field-sensitivity)

- Graph is a higher-level abstraction extracted from the LLVM IR indicating ***where*** pointer analysis should be performed.
- Rules defines ***how*** to derive the points-to information from each statement,
- Solver determines in ***what*** order to resolve all the constraints.

More details can be found at `https://goo.gl/msaVba`.

SVF Overview





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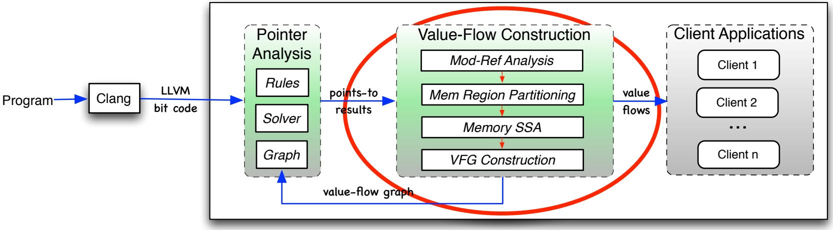
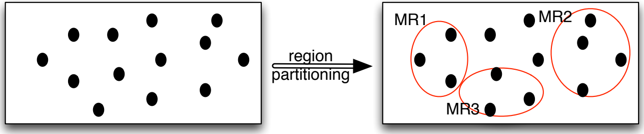
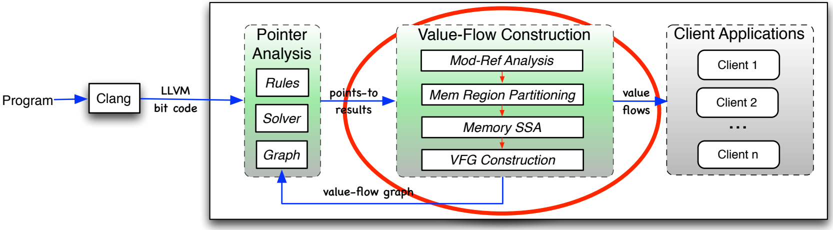




Partition the memory objects into memory regions are accessed equivalently

SVF Overview

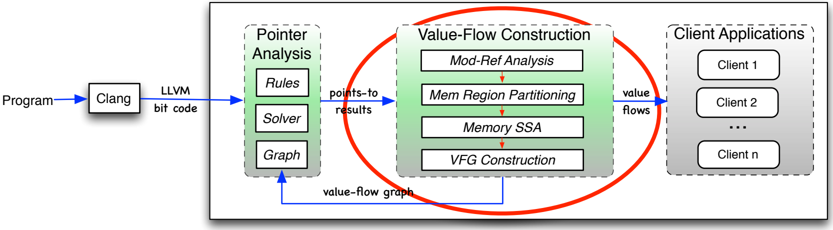


Interprocedural memory SSA construction based on HSSA (CC '96[a]) and widely used in Open64.

- **Side-Effect Annotation** at loads/stores and callsites
- **Placing Memory SSA** ϕ for memory regions.
- **SSA Renaming** for regions with different versions:

[a] F Chow, S Chan, SM Liu, R Lo, M Streich, *Effective representation of aliases and indirect memory operations in SSA form*, CC 1996

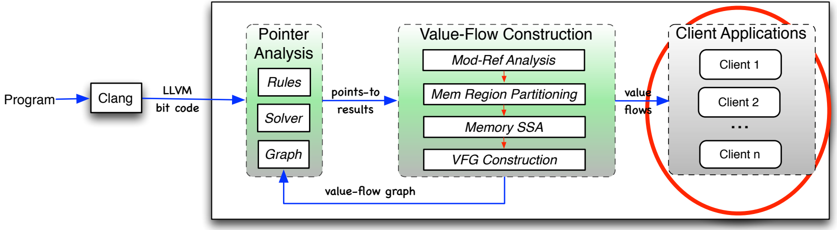
SVF Overview



Value-Flow Construction:

- **Direct Value-Flows**: def-use of top-level pointers
- **Indirect Value-Flows**: def-use of address-taken variables based on memory SSA

SVF Overview



- Advanced pointer analyses (SAS '14, SPE '14, CGO '16)
- Memory leak detection (ISSTA '12, TSE '14, SAC '16)
- Accelerating dynamic analysis including temporal memory safety (CGO '14), spatial memory safety (ISSRE '14, TOR '16)
- Value-flow analysis for multithreaded programs(ICPP '15, CGO '16, PMAM '16)

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Andersen's Pointer Analysis

SVF transforms LLVM instructions into a graph representation

Constraint Graph (Design doc: `https://goo.gl/Q8mxFw`)

- Node:
  - A pointer: (LLVM Value in pointer type)
  - An object: (heap, stack, global, function)
- Edge: A Constraint between two nodes

Address	$p = alloc_{obj}$
Copy	$p = q$
Load	$p = *q$
Store	$*p = q$
Field	$p = q$ *gep* f

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Address	p = alloc_{obj}	$\{obj\} \subseteq \text{Pts}(p)$
Copy	p = q	$\text{Pts}(p) \subseteq \text{Pts}(p)$
Load	p = *q	$\forall o \in \text{Pts}(q), \text{Pts}(o) \subseteq \text{Pts}(p)$
Store	*p = q	$\forall o \in \text{Pts}(p), \text{Pts}(q) \subseteq \text{Pts}(o)$
Field	p = q *gep* f	$\forall o \in \text{Pts}(q), o.f \subseteq \text{Pts}(p)$

Andersen's Pointer Analysis

```
struct st{
        char f1;
        char f2;
};
typedef struct st ST;

int main(){
        char a1; ST st;
        char *a = &a1;
        char *b = &(st.f2);
        swap(&a,&b);
}
void swap(char **p, char **q){
        char* t = *p;
        *p = *q;
        *q = t;
}
```

```
define i32 @main() {
entry:
        %a = alloca i8*, align 8                   // O1
        %b = alloca i8*, align 8                   // O2
        %a1 = alloca i8, align 1                   // O3
        %st = alloca %struct.st, align 1           // O4
        store i8* %a1, i8** %a, align 8
        %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
        store i8* %f2, i8** %b, align 8
        call void @swap(i8** %a, i8** %b)
        ret i32 0
}
define void @swap(i8** %p, i8** %q) {
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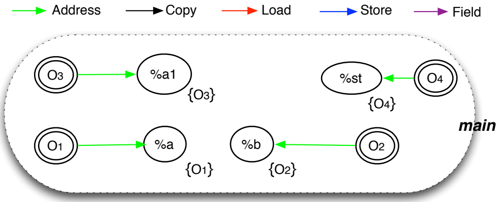
LLVM IR



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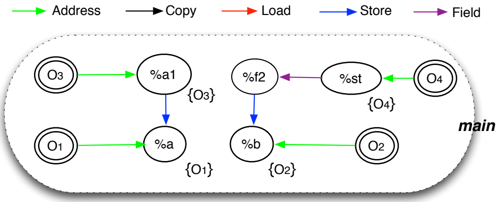

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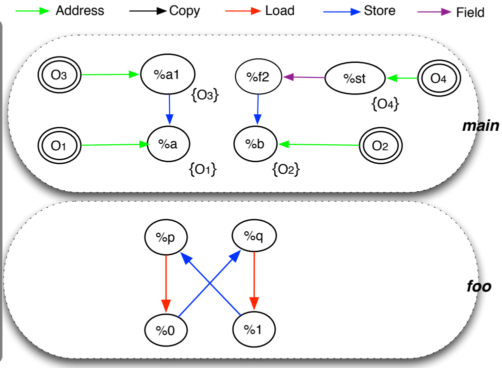

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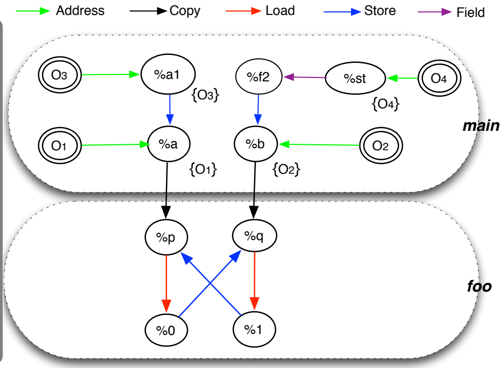

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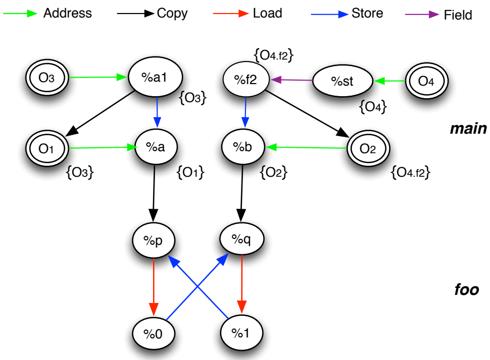

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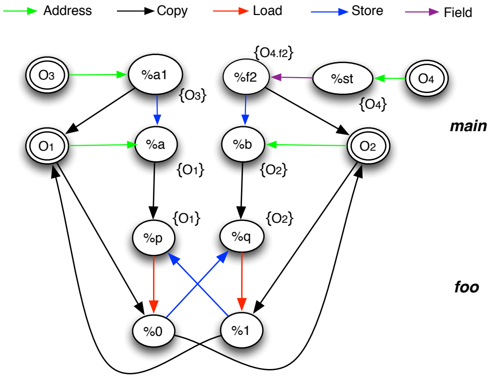

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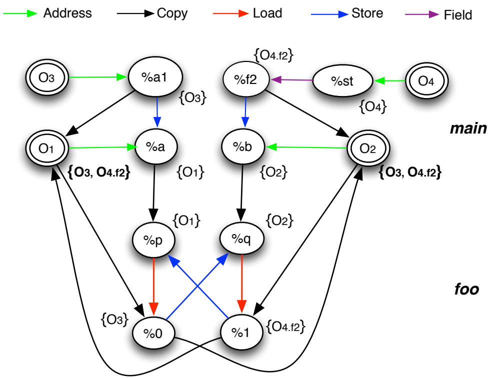

Constraint Graph

Constraint solving techniques: Wave-Deep Propagation, HCD, LCD. More details can be found here

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Memory SSA

Memory SSA is constructed per procedure given the global points-to information after region partitioning.

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- Side-effect annotation.
  - **Load**: $p = *q$ is annotated with a $\mu(o)$ for each variable $o \in \mathrm{Pts}(q)$.
  - **Store**: $*p = q$ is annotated with a $o = \chi(o)$ for each variable $o \in \mathrm{Pts}(p)$.
  - **Callsite**: *foo*(...) is annotated with $\mu(o)/\chi(o)$ if o is referred or modified inside caller *foo*.
  - **Function entry/exit**: $\chi(o)/\mu(o)$ is annotated at the entry of a function (e.g., foo) if o is referred or modified in *foo*.

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  - **Function entry/exit**: $\chi(o)/\mu(o)$ is annotated at the entry of a function (e.g., foo) if o is referred or modified in *foo*.
- Memory SSA construction
  - **Placing Memory SSA** ϕ for memory objects.
  - **Renaming** objects with different versions:
    - $\mu(o)$ is treated as a use of o.
    - $o = \chi(o)$ is treated as both a def and a use of o.

Memory SSA

```
define i32 @main() {
entry:
        %a = alloca i8*, align 8                    // O1
        %b = alloca i8*, align 8                    // O2
        %a1 = alloca i8, align 1                    // O3
        %st = alloca %struct.st, align 1            // O4
        store i8* %a1, i8** %a, align 8
        %f2 = getelementptr ... %st, i32 0, i32 1
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        call void @swap(i8** %a, i8** %b)
        ret i32 0
}
define void @swap(i8** %p, i8** %q) {
entry:
        %0 = load i8** %p, align 8
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        store i8* %1, i8** %p, align 8
        store i8* %0, i8** %q, align 8
        ret void
}
```

LLVM IR

Annotation

```
========FUNCTION: main========
entry
 %a = alloca i8*, align 8              // O1
 %b = alloca i8*, align 8              // O2
 %a1 = alloca i8, align 1              // O3
 %st = alloca %struct.st, align 1      // O4

 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr ... %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)

 ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
 %0 = load i8*, i8** %p, align 8

LDMU(MR2V_1)
 %1 = load i8*, i8** %q, align 8

 store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

Memory SSA

```
=======FUNCTION: main=======
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 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
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 ret i32 0
=======FUNCTION: swap=======
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LDMU(MR1V_1)
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MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR of the example code

Pre-computed Points-to:

pt(%a) = pt(%p) = {O1}
pt(%b) = pt(%q) = {O2}

Memory Region:

MR2: O2
MR1: O1

Annotated CHIs at stores

Memory SSA

```
=======FUNCTION: main=======
entry
 %a = alloca i8*, align 8           // O1
 %b = alloca i8*, align 8           // O2
 %a1 = alloca i8, align 1           // O3
 %st = alloca %struct.st, align 1  // O4

 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)

 ret i32 0
=======FUNCTION: swap=======
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
 %0 = load i8*, i8** %p, align 8

LDMU(MR2V_1)
 %1 = load i8*, i8** %q, align 8

 store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR of the example code

Pre-computed Points-to:

pt(%a) = pt(%p) = {O1}
pt(%b) = pt(%q) = {O2}

Memory Region:

MR2: O2
MR1: O1

Annotated MUs at loads

Memory SSA

```
========FUNCTION: main========
entry
 %a = alloca i8*, align 8           // O1
 %b = alloca i8*, align 8           // O2
 %a1 = alloca i8, align 1           // O3
 %st = alloca %struct.st, align 1  // O4

 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)

 ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
 %0 = load i8*, i8** %p, align 8

LDMU(MR2V_1)
 %1 = load i8*, i8** %q, align 8

 store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR of the example code

Pre-computed Points-to:

pt(%a) = pt(%p) = {O1}
pt(%b) = pt(%q) = {O2}

Memory Region:

MR2: O2
MR1: O1

Annotated MUs/CHIs at callsite

Memory SSA

```
========FUNCTION: main========
entry
 %a = alloca i8*, align 8            // O1
 %b = alloca i8*, align 8            // O2
 %a1 = alloca i8, align 1            // O3
 %st = alloca %struct.st, align 1    // O4

 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)

 ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
 %0 = load i8*, i8** %p, align 8

LDMU(MR2V_1)
 %1 = load i8*, i8** %q, align 8

 store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR of the example code

Pre-computed Points-to:

pt(%a) = pt(%p) = {O1}
pt(%b) = pt(%q) = {O2}

Memory Region:

MR2: O2
MR1: O1

Annotated MUs/CHIs at Function entry/exit

Memory SSA

```
define i32 @main() {
entry:
        %a = alloca i8*, align 8                  // O1
        %b = alloca i8*, align 8                  // O2
        %a1 = alloca i8, align 1                  // O3
        %st = alloca %struct.st, align 1          // O4
        store i8* %a1, i8** %a, align 8
        %f2 = getelementptr ... %st, i32 0, i32 1
        store i8* %f2, i8** %b, align 8
        call void @swap(i8** %a, i8** %b)
        ret i32 0
}
define void @swap(i8** %p, i8** %q) {
entry:
        %0 = load i8** %p, align 8
        %1 = load i8** %q, align 8
        store i8* %1, i8** %p, align 8
        store i8* %0, i8** %q, align 8
        ret void
}
```

LLVM IR

Annotation

```
========FUNCTION: main========
entry
 %a = alloca i8*, align 8              // O1
 %b = alloca i8*, align 8              // O2
 %a1 = alloca i8, align 1              // O3
 %st = alloca %struct.st, align 1      // O4

 store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)

 %f2 = getelementptr ... %st, i32 0, i32 1
 store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)

CALMU(MR1V_2)
CALMU(MR2V_2)
 call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)

 ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
 %0 = load i8*, i8** %p, align 8

LDMU(MR2V_1)
 %1 = load i8*, i8** %q, align 8

 store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)

 store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)

 ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

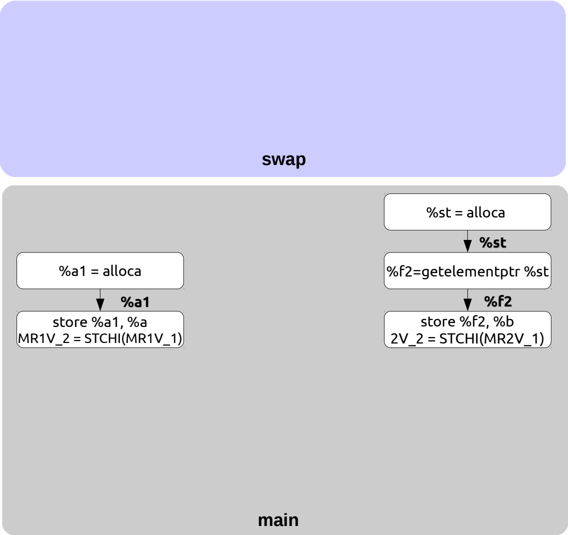
Outline

- Static Value-Flow
- SVF Overview
- SVF Internals
  - Pointer Analysis
  - Interprocedural Memory SSA
  - Value-Flow Construction
  - Supporting Multithreaded Programs
- Results and Client Applications

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8              // O1
  %b = alloca i8*, align 8              // O2
  %a1 = alloca i8, align 1              // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

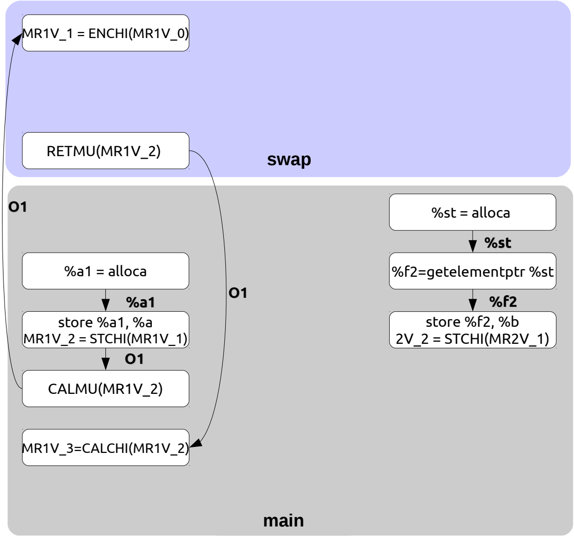


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8            // O1
  %b = alloca i8*, align 8            // O2
  %a1 = alloca i8, align 1            // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

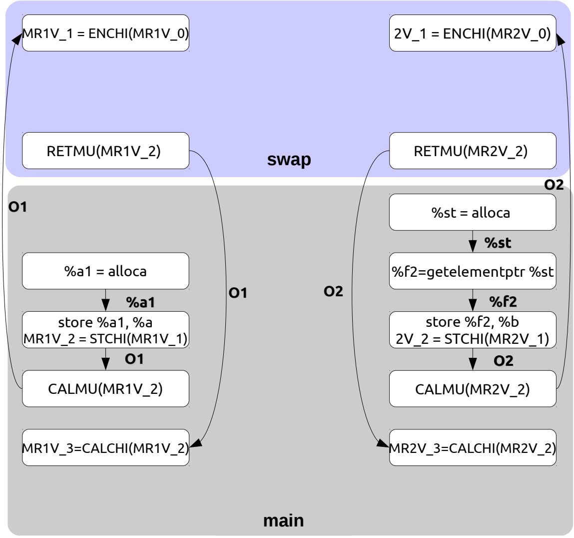


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8          // O1
  %b = alloca i8*, align 8          // O2
  %a1 = alloca i8, align 1          // O3
  %st = alloca %struct.st, align 1  // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

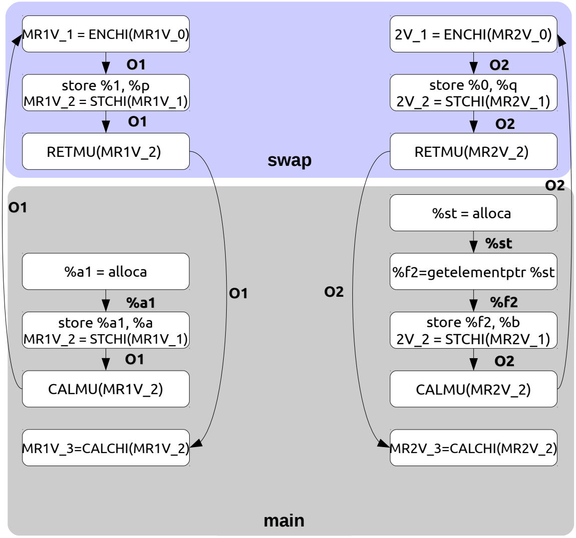


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8             // O1
  %b = alloca i8*, align 8             // O2
  %a1 = alloca i8, align 1             // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

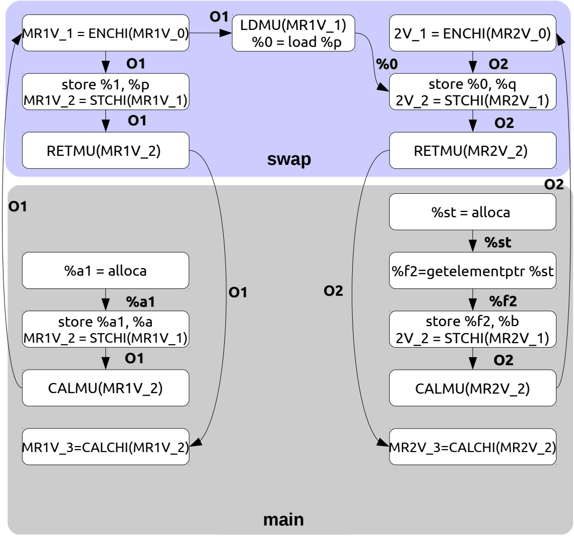


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8                // O1
  %b = alloca i8*, align 8                // O2
  %a1 = alloca i8, align 1                // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

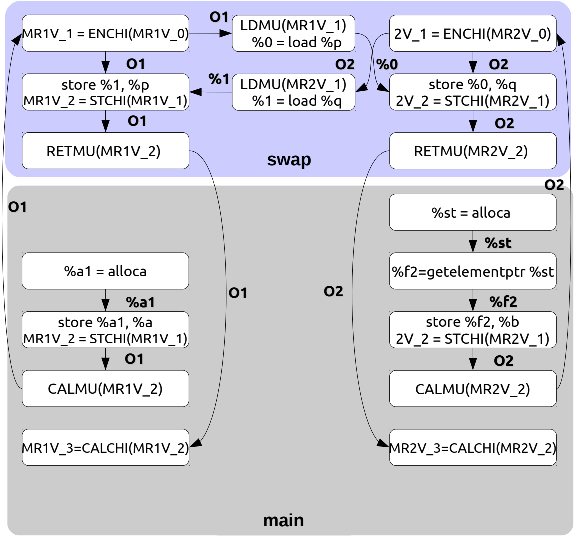


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8              // O1
  %b = alloca i8*, align 8              // O2
  %a1 = alloca i8, align 1              // O3
  %st = alloca %struct.st, align 1      // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR



Value-Flow Graph

Interprocedural Value-Flow

```c
struct st{
      char f1;
      char f2;
};
typedef struct st ST;

int main(){
      char a1; ST st;
      char *a = &a1;
      char *b = &(st.f2);
      swap(&a,&b);
}
void swap(char **p, char **q){
      char* t = *p;
      *p = *q;
      *q = t;
}
```

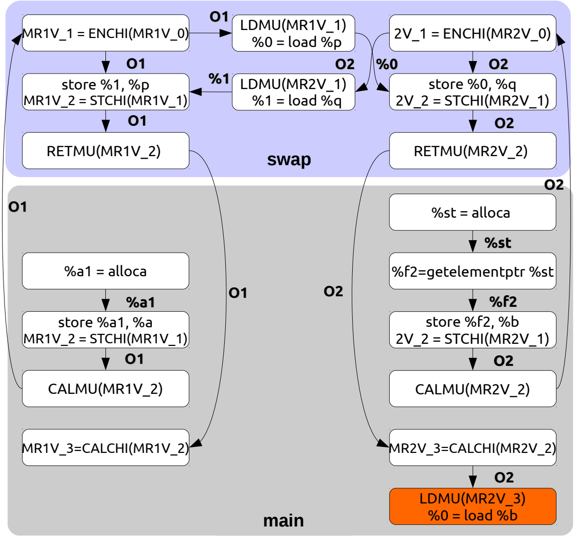
Query: b ?

```llvm
define i32 @main() {
entry:
      %a = alloca i8*, align 8                 // O1
      %b = alloca i8*, align 8                 // O2
      %a1 = alloca i8, align 1                 // O3
      %st = alloca %struct.st, align 1         // O4
      store i8* %a1, i8** %a, align 8
      %f2 = getelementptr inbounds %struct.st, %struct.st* %st, i32 0, i32 1
      store i8* %f2, i8** %b, align 8
      call void @swap(i8** %a, i8** %b)
      ret i32 0
}
define void @swap(i8** %p, i8** %q) {
entry:
      %0 = load i8** %p, align 8
      %1 = load i8** %q, align 8
      store i8* %1, i8** %p, align 8
      store i8* %0, i8** %q, align 8
      ret void
}
```

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8            // O1
  %b = alloca i8*, align 8            // O2
  %a1 = alloca i8, align 1            // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

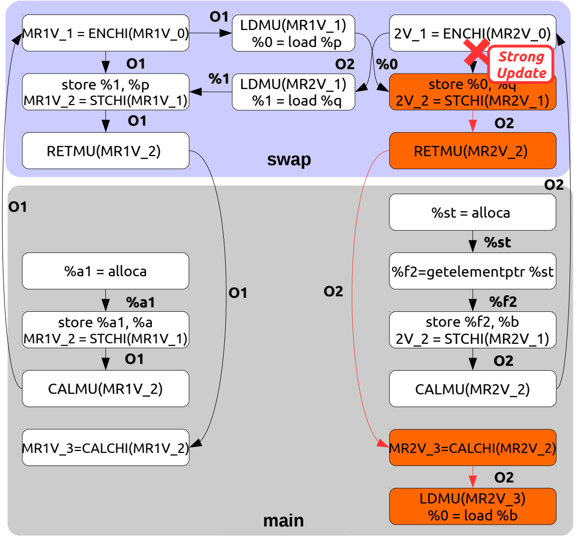


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8             // O1
  %b = alloca i8*, align 8             // O2
  %a1 = alloca i8, align 1             // O3
  %st = alloca %struct.st, align 1 // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

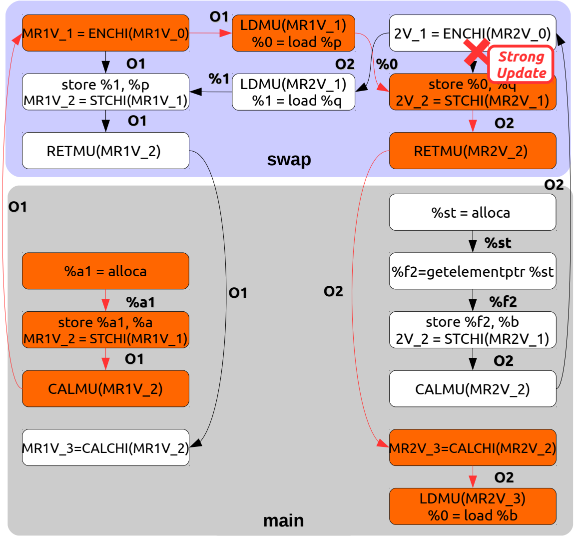


Value-Flow Graph

Interprocedural Value-Flow

```
========FUNCTION: main========
entry
  %a = alloca i8*, align 8              // O1
  %b = alloca i8*, align 8              // O2
  %a1 = alloca i8, align 1              // O3
  %st = alloca %struct.st, align 1      // O4
  store i8* %a1, i8** %a, align 8
MR1V_2 = STCHI(MR1V_1)
  %f2 = getelementptr ... %st, ...
  store i8* %f2, i8** %b, align 8
MR2V_2 = STCHI(MR2V_1)
CALMU(MR1V_2)
CALMU(MR2V_2)
  call void @swap(i8** %a, i8** %b)
MR1V_3 = CALCHI(MR1V_2)
MR2V_3 = CALCHI(MR2V_2)
LDMU(MR2V_3)
  %0 = load i8*, i8** %b
  ret i32 0
========FUNCTION: swap========
MR1V_1 = ENCHI(MR1V_0)
MR2V_1 = ENCHI(MR2V_0)
entry
LDMU(MR1V_1)
  %0 = load i8*, i8** %p, align 8
LDMU(MR2V_1)
  %1 = load i8*, i8** %q, align 8
  store i8* %1, i8** %p, align 8
MR1V_2 = STCHI(MR1V_1)
  store i8* %0, i8** %q, align 8
MR2V_2 = STCHI(MR2V_1)
  ret void
RETMU(MR1V_2)
RETMU(MR2V_2)
```

Annotated IR

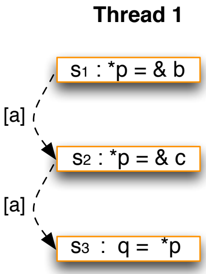


Value-Flow Graph

Outline

- Static Value-Flow
- SVF Overview
- SVF Internals
  - Pointer Analysis
  - Interprocedural Memory SSA
  - Value-Flow Construction
  - Supporting Multithreaded Programs
- Results and Client Applications

Value-Flow Under Thread Interleaving



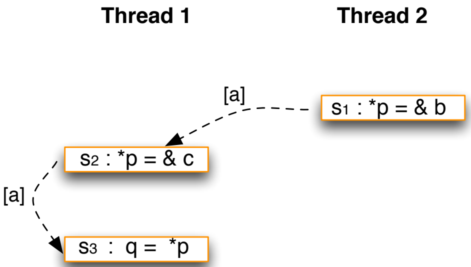
Value-Flow Under Thread Interleaving

Thread 1	**Thread 2**
fork(t2, foo) →	foo(){
	s_1 : *p = & b
s_2 : *p = & c	}
s_3 : q = *p	

Interleaving

Value-Flow Under Thread Interleaving

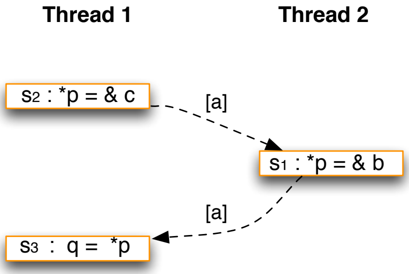
Scenario 1:



execution sequence : s_1, s_2, s_3

Value-Flow Under Thread Interleaving

Scenario 2:



execution sequence : s_1, s_2, s_3

execution sequence : s_2, s_1, s_3

Value-Flow Under Thread Interleaving

Scenario 3:

Thread 1	Thread 2
s_2 : *p = & c	
[a] ↓	
s_3 : q = *p	
	s_1 : *p = & b

execution sequence : s_1, s_2, s_3

execution sequence : s_2, s_1, s_3

execution sequence : s_2, s_3, s_1

Value-Flow Under Thread Interleaving

Thread 1

$\boxed{\text{fork(t2, foo)}}$

$\boxed{\text{join(t2)}}$

s_2 : *p = & c

s_3 : q = *p

Thread 2

foo(){

s_1 : *p = & b

}

(a) non-interference via join

Thread 1

$\boxed{\text{fork(t2, foo)}}$

$\boxed{\text{lock(l)}}$

s_2 : *p = & c

s_3 : q = *p

$\boxed{\text{unlock(l)}}$

Thread 2

foo(){

$\boxed{\text{lock(l)}}$

s_1 : *p = & b

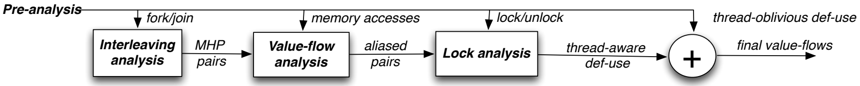
$\boxed{\text{unlock(l)}}$

}

(b) non-interference via lock/unlock

Supporting Multithreaded Programs (CGO '16)

- Thread-oblivious value-flows(Ignore Pthread APIs)
- Thread-aware value-flows
  - Fork-join
  - Memory access
  - Lock/unlock



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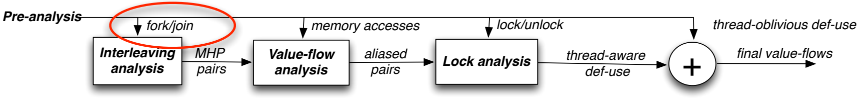

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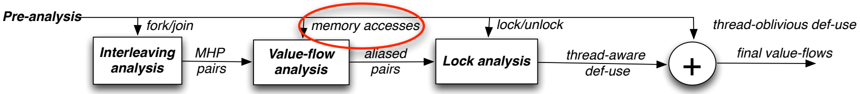

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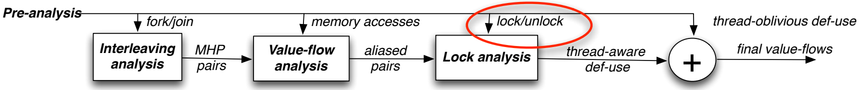

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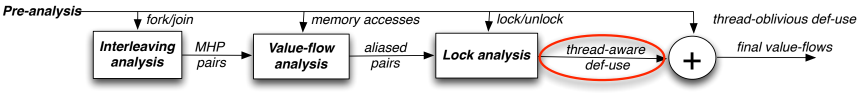

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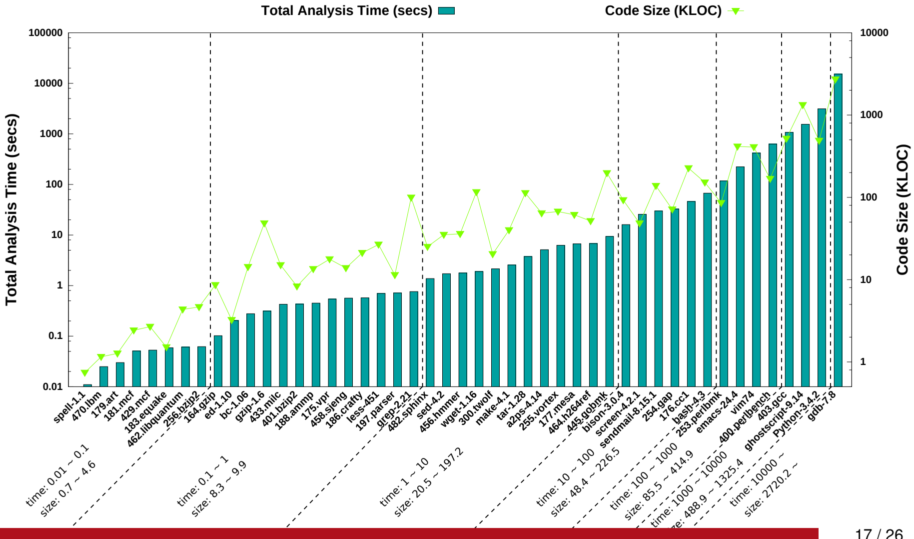
Evaluation and Results

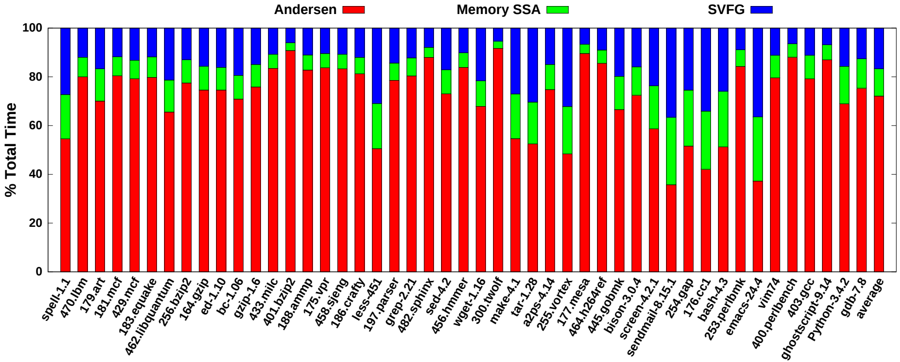
- Benchmarks:
  - All SPEC C benchmarks: 15 programs from CPU2000 and 12 programs from CPU2006
  - 20 Open-source applications: most of them are recent released versions.
  - Total lines of code evaluated: 8,005,872 LOC with maximum program size 2,720,279 LOC
  - Gold Plugin is used to combine multiple bitcode files into one
- Machine setup:
  - Ubuntu Linux 3.11.0-15-generic Intel Xeon Quad Core HT, 3.7GHZ, 64GB

Analysis Time

Total Analysis Time = Andersen + MemorySSA + VFG

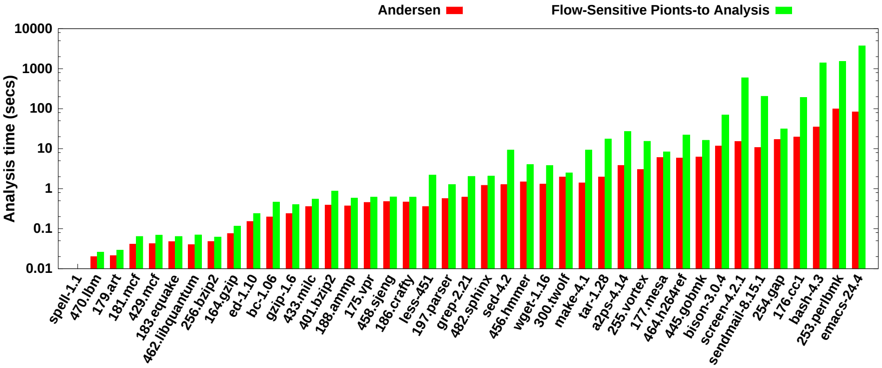


Analysis Time Distribution



Average Percentage: Andersen (71.9%), Memory SSA (11.3%), VFG (16.8%)

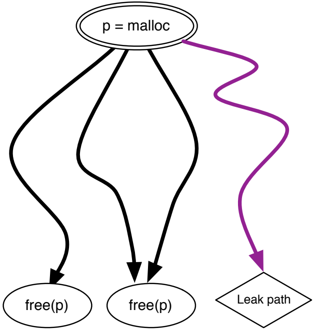
Analysis Time : Andersen v.s. Flow-Sensitive Points-to Analysis



Flow-Sensitive Analysis Slowdowns: From $1.2\times$ to $44\times$. On average $6.5\times$.

Client 1: Memory Leak Detection (TSE ’14, ISSTA ’12)

- **Source-Sink Problem**: every object created at an allocation site (**a source**) must eventually reach one free site (**a sink**) during any program execution path.



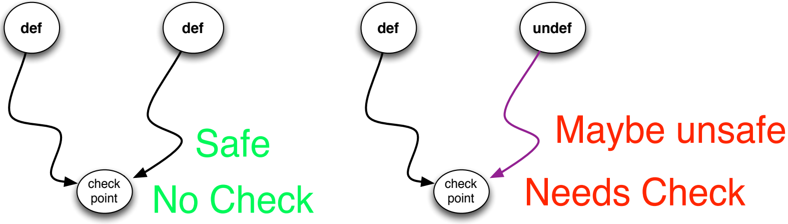
Client 1: Memory Leak Detection (TSE '14, ISSTA '12)

Leak Detector	Speed (LOC/sec)	Bug Count	FP Rate(%)
ATHENA	50	53	10
CONTRADICTION	300	26	56
CLANG	400	27	25
SPARROW	720	81	16
FASTCHECK	37,900	59	14
SABER	**10,220**	**85**	**19**

Comparing SABER with other static detectors on analysing SPEC2000 C programs

Client 2: Accelerating Memory Sanitizer (CGO '14)

- Detecting uninitialized variables using source-level instrumentation on LLVM IR[1].



There is no value-flow reachable from an undefined allocation sites

Reachable from an undefined allocation sites along at least one value-flow path

[1] *In C, global variables are default-initialized but local and heap variables are not*

Client 2: Accelerating Memory Sanitizer (CGO '14)

- Usher^{TL}: Direct value-flow via only top-level pointers.
- Usher^{AT}: Direct and indirect value-flow via both top-level and address-taken variables.
- Usher^{Op1}: Reduce shadow propagation. $X \rightarrow Y \rightarrow Z$ reduced to $X \rightarrow Z$.
- Usher: Redundant check elimination. Check c is redundant if all checks flow to c is checked (e.g., double checking *p along control flow).

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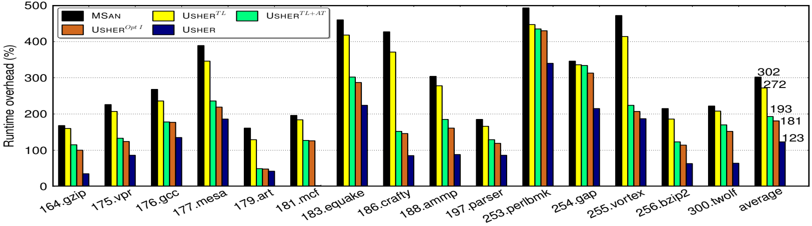
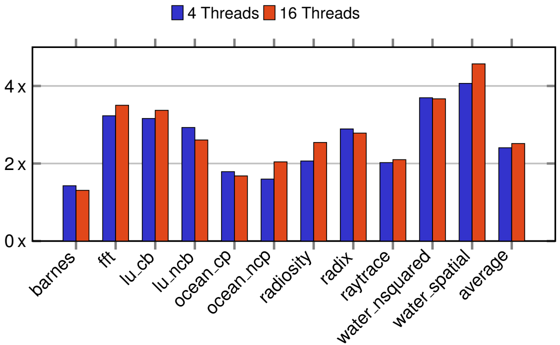


Execution time slowdowns (normalized with respect to native code).

Client 3: Accelerating Thread Sanitizer (PMAM ’16)

A check for a memory access is redundant if it has no outgoing or incoming inter-thread (thread-aware) value-flows.

- ThreadLocal
- MHP analysis + Alias analysis + Lock Analysis



Speedups over original TSan (under -O0).

Conclusion and Future Work

- Conclusion
  - A research tool supports refinement-based interprocedural program dependence analysis on top of LLVM
  - Pointer analysis variants
  - Interprocedural memory SSA
  - Value-flow construction
- Future work
  - Advanced Static Analysis
    - C++/Objective-C Support
    - Demand-driven flow-, context- and heap- sensitive analysis (*coming soon*)
  - Bug Detection
    - Use-after-free detection
    - Enforcement of fine-grained control flow integrity (CFI)
    - Accelerating dynamic symbolic execution (Klee or Fuzzer etc.)

- Publicly available open source of SVF (LLVM License)
  `http://unsw-corg.github.io/SVF/`
- Micro benchmarks to validate the correctness of analyses
  `https://github.com/unsw-corg/PTABen`
- A simple Eclipse Plugin
  `https://github.com/unsw-corg/SVF-EclipsePlugin`

Thanks!

Q & A