LINUX PLUMBERS CONFERENCE | SEPTEMBER 20-24, 2021

Soufflé, Points-To Analysis and Data Layout Optimizations

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What is Soufflé?

https://souffle-lang.github.io/

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.input edge
.decl path(x:number, y:number)
.output path
path(x, y) :- edge(x, y).
path(x, y) :- path(x, z), edge(z, y).
```

https://souffle-lang.github.io/simple

What is Soufflé?

Figure 2. Staged Compilation Framework for Synthesizing C++ Programs from a Datalog Specification

Scholz, Bernhard, et al. "On fast large-scale program analysis in datalog." Proceedings of the 25th International Conference on Compiler Construction. 2016.

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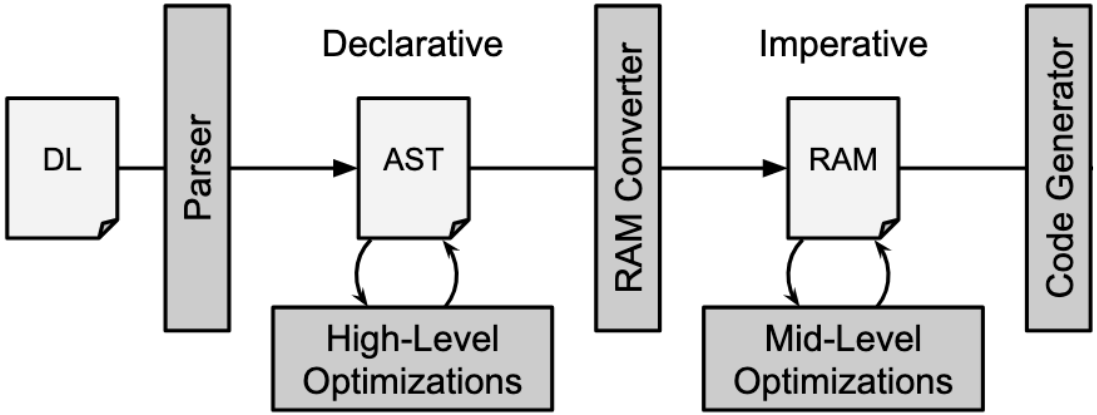

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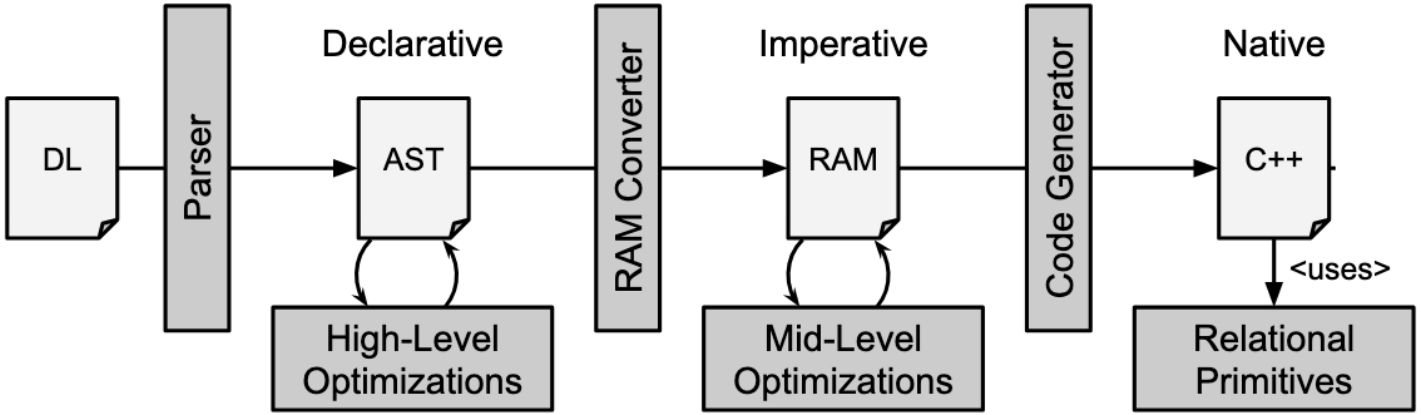

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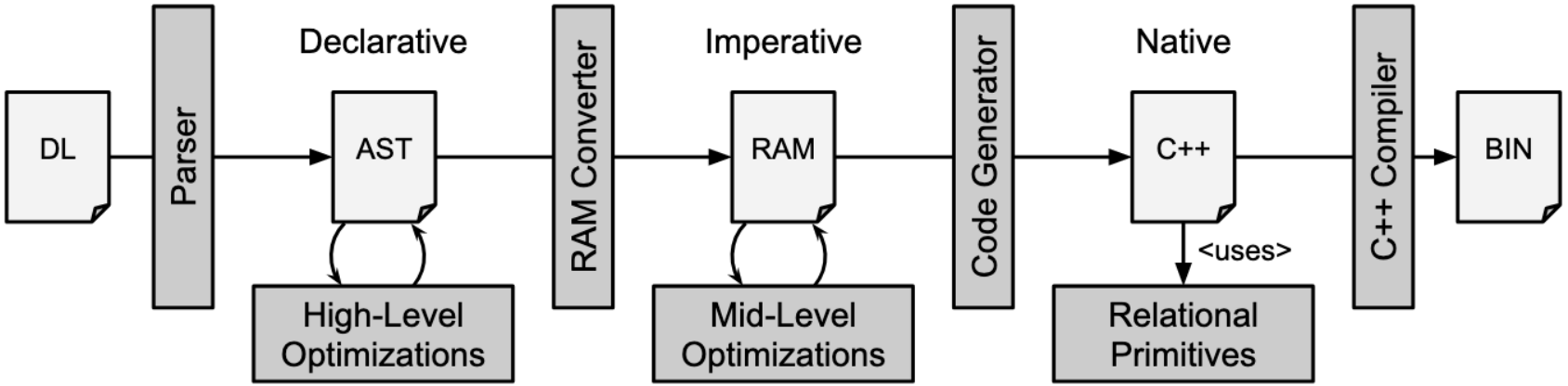

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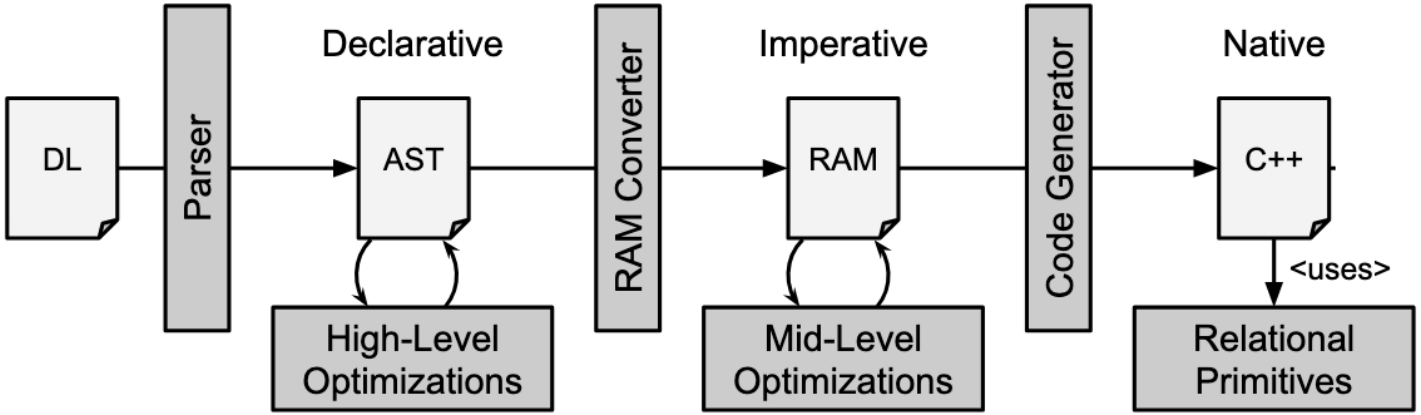

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Why do we think Soufflé is interesting?

1. Datalog is a language well suited for program analysis.
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Can Soufflé programs be part of the GCC build process?

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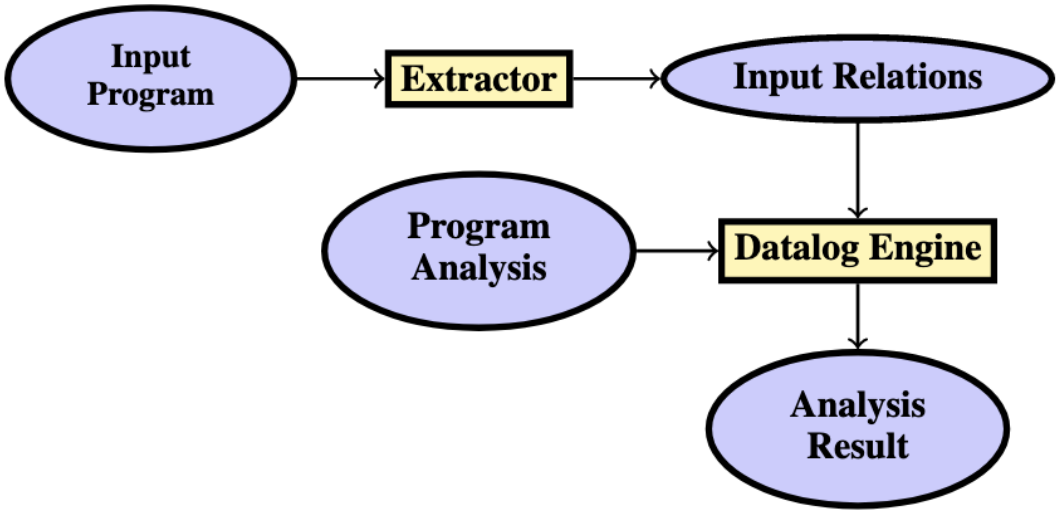

Figure 1. Typical Program Analysis in Datalog using an Extractor

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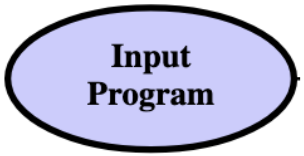

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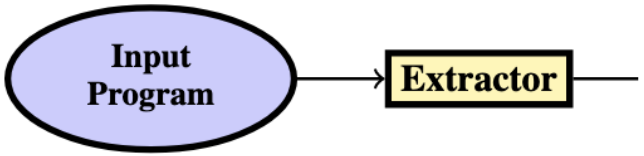

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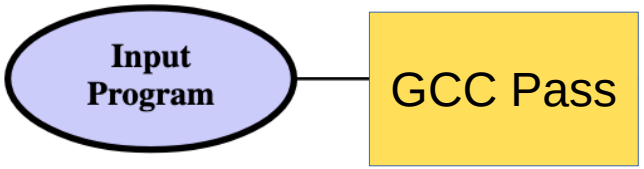

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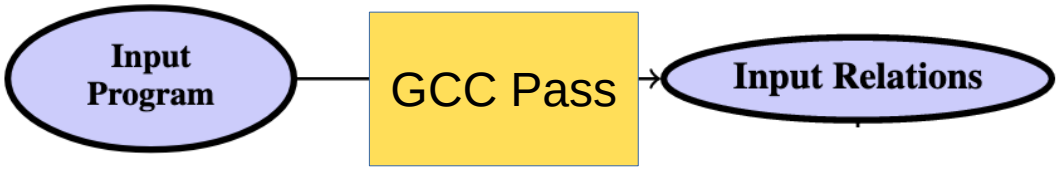

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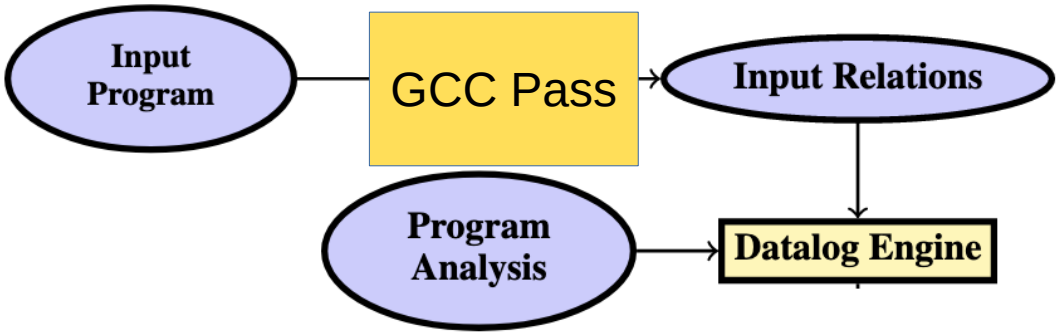

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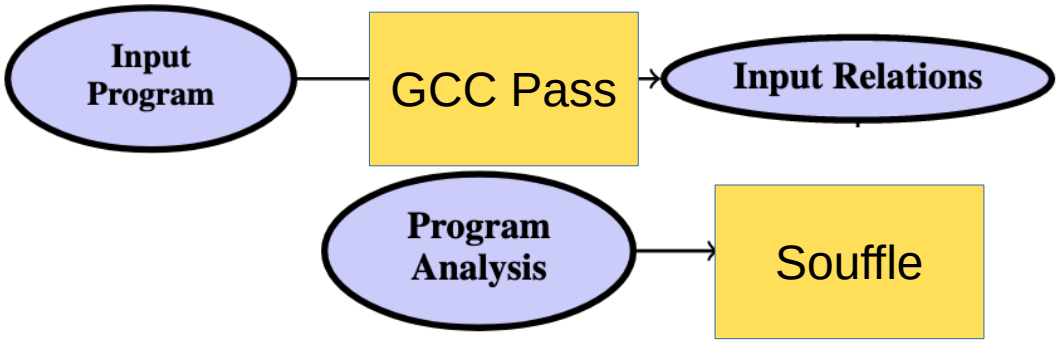

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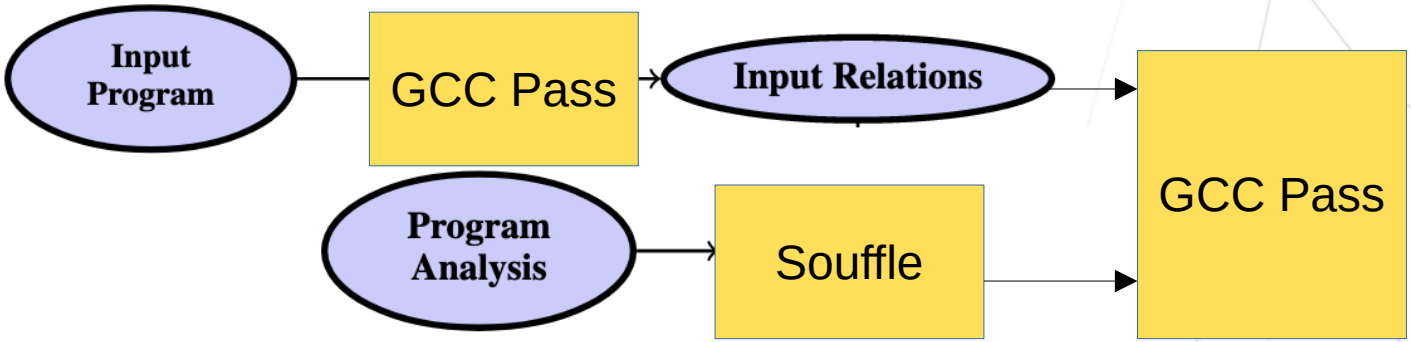

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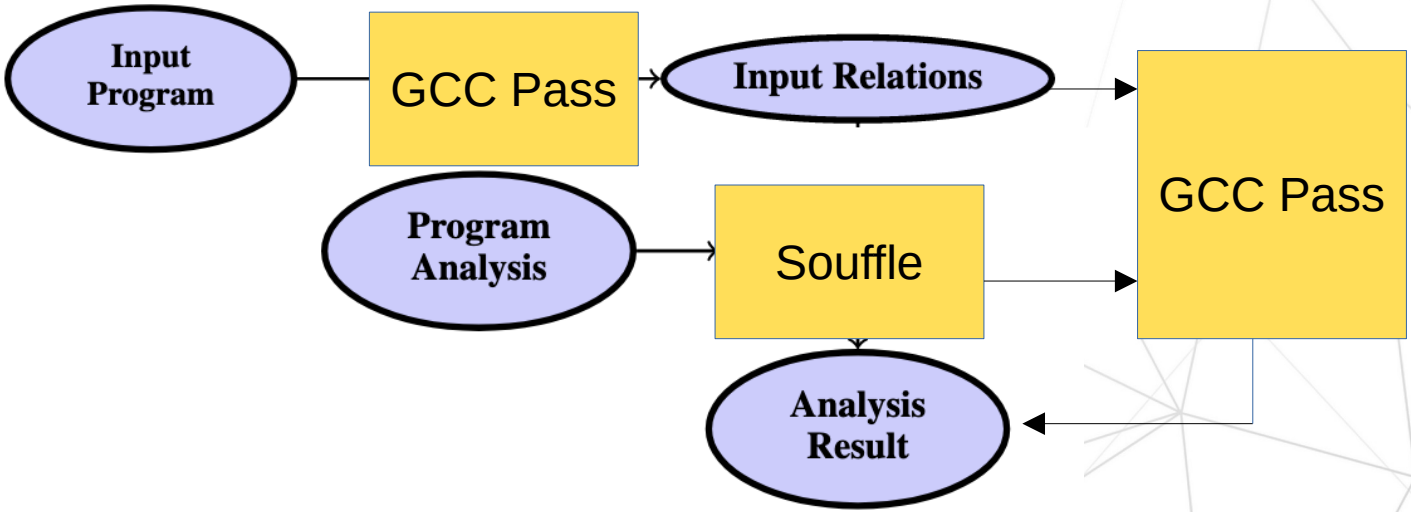

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Motivation for LTO Points-To Analysis implementation in Soufflé

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```
struct arc
{
  int id;
  cost_t cost;
  node_p tail, head;
  short ident;
  arc_p nextout, nextin;
  flow_t flow;
  cost_t org_cost;
};
```

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```
struct node {
  cost_t potential;
  int orientation;
  node_p child, pred, sibling, sibling_prev;
  arc_p basic_arc, firstout, firstin, arc_tmp;
  flow_t flow;
  LONG depth;
  int number;
  int time;
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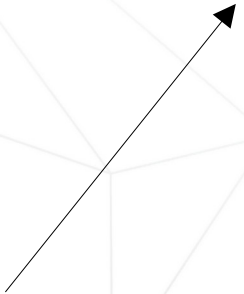

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  flow_t flow;
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};
```

72

```
struct node {
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  flow_t flow;
  LONG depth;
  int orientation;
  int number;
  int time;
};
```

104

Motivation for LTO Points-To Analysis implementation in Soufflé

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struct arc
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  cost_t org_cost;
  flow_t flow;
  int id;
  short ident;
};
```

72 → 56

```
struct node {
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  flow_t flow;
  LONG depth;
  int orientation;
  int number;
  int time;
};
```
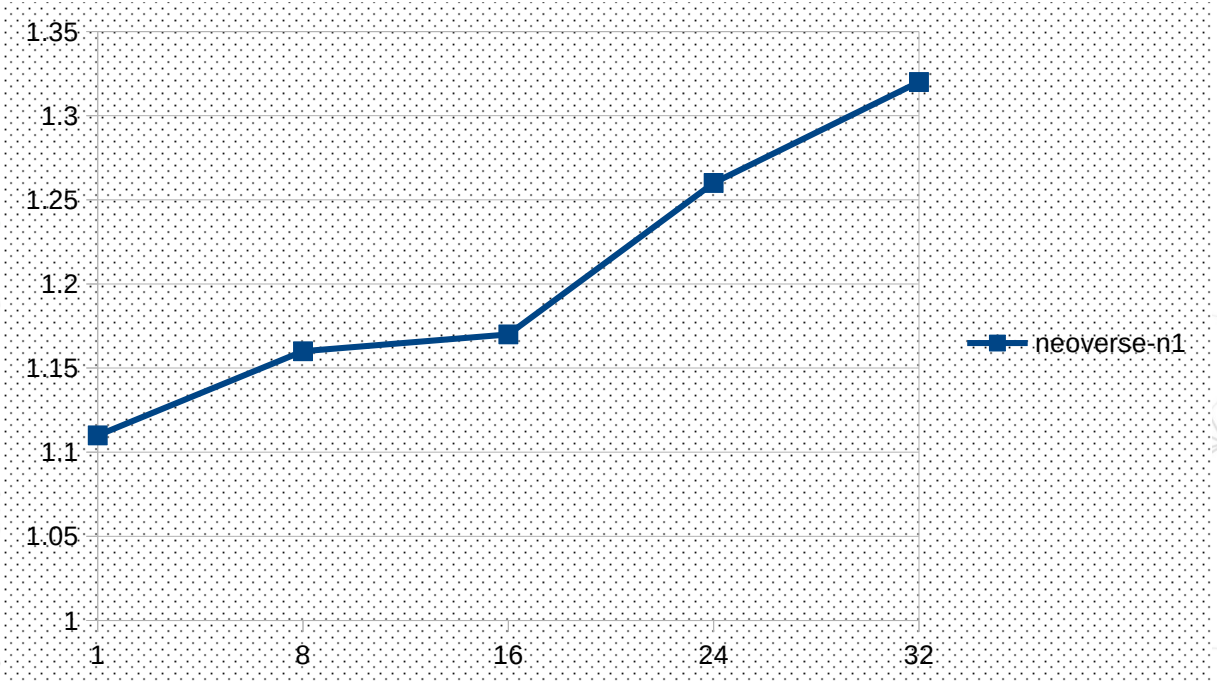

104 → 96

Normalized MCF score



Type Escape vs Points-To Analysis

Points To Analysis	Type Escape Analysis
Can be applied at an alias-level granularity.	Can only be applied to all instances of a given type.
Harder to implement.	Easier to implement.

Majority of current implementation

```
PointsTo (pointer, pointee) :- PA (pointer, _, pointee, _).

PointsTo (pointer, pointee) :- PP (pointer, _, temp, _)
  , PointsTo (temp, pointee).

PP (left, 0, right, 0) :- PS (left, _, temp, _)
  , PointsTo (temp, right).

PP (left, 0, right, 0) :- SP (temp, _, right, _)
  , PointsTo (temp, left).

PA (left, 0, pointee, 0) :- SA (temp, _, pointee, _)
  , PointsTo (temp, left).

PS (left, 0, right, 0) :- SS (temp, _, right, _)
  , PointsTo (temp, left).
```

Majority of current implementation

PointsTo (pointer, pointee) :-
PA (pointer, _, pointee, _).

pointer = &pointee

Majority of current implementation

```
pointer = temp;
```

Majority of current implementation

:- PP (pointer, _, temp, _)

pointer = temp;

Majority of current implementation

:- PP (pointer, _, temp, _)

temp = &pointee;
pointer = temp;

Majority of current implementation

```
:- PP (pointer, _, temp, _)
, PointsTo (temp, pointee).
```

```
temp = &pointee;
pointer = temp;
```

Majority of current implementation

```
PointsTo (pointer, pointee)
  :- PP (pointer, _, temp, _)
  , PointsTo (temp, pointee).

temp = &pointee;
pointer = temp;
```

Majority of current implementation

```
left = *temp;
```

Majority of current implementation

:- PS (left, _, temp, _)

left = *temp;

Majority of current implementation

```
:- PS (left, _, temp, _)
, PointsTo (temp, right).
```

```
temp = &right;
left = *temp;
```

Majority of current implementation

```
PP (left, 0, right, 0)
  :- PS (left, _, temp, _)
  , PointsTo (temp, right).

temp = &right;
left = *temp;
// left = right;
```

Majority of current implementation

```
PointsTo (pointer, pointee) :- PA (pointer, _, pointee, _).

PointsTo (pointer, pointee) :- PP (pointer, _, temp, _)
  , PointsTo (temp, pointee).

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```

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2. There needs to be a dialogue on the possibility of integrating Soufflé generated code to GCC's code base

1. Soufflé is an exciting possible new direction for program analysis
2. There needs to be a dialogue on the possibility of integrating Soufflé generated code to GCC's code base
3. We are currently working on a points-to analysis to resolve concerns on our previous data layout optimization implementation.

Bibliography

1. Golovanevsky, Olga, and Ayal Zaks. "Struct-reorg: current status and future perspectives." Proceedings of the GCC Developers' Summit. 2007.
2. Zhao, Peng, et al. "Forma: A framework for safe automatic array reshaping." ACM Transactions on Programming Languages and Systems (TOPLAS) 30.1 (2007): 2-es.
3. Yong, Suan Hsi, Susan Horwitz, and Thomas Reps. "Pointer analysis for programs with structures and casting." ACM SIGPLAN Notices 34.5 (1999): 91-103.
4. Balatsouras, George, and Yannis Smaragdakis. "Structure-sensitive points-to analysis for C and C++." International Static Analysis Symposium. Springer, Berlin, Heidelberg, 2016

Questions

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Materials for Questions

Why not extend current IPA-PTA instead of implementing a new one?
What does a points-to analysis that handles cast look like?
How does type escape analysis differs from a points-to analysis?
How does GCC feeds constraints to the souffle program?
How are the constraints generated?
Can you show more of the Souffle code?
How is cast-aware points-to analysis implemented?

Comparing Points-To Analysis

GCC IPA-PTA	PTA in Forma Paper
Inter-procedural	
Field Sensitive	
Flow Insensitive	
Context Insensitive	
Inclusion-Based	Unification-Based
Cast Unaware	Cast Aware

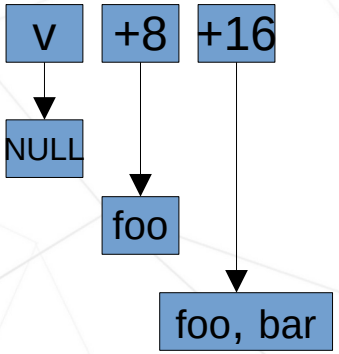
Cast-(Un)Aware

```
struct s  { long *a; long *b; long *c;};

struct s v;

v.a = NULL;                     // v +  0 ⊇ NULL
v.b = &foo;                     // v +  8 ⊇ foo
v.c = cond ? &foo : &bar;       // v + 16 ⊇ foo
                                // v + 16 ⊇ bar


// What does v.b points-to?
```



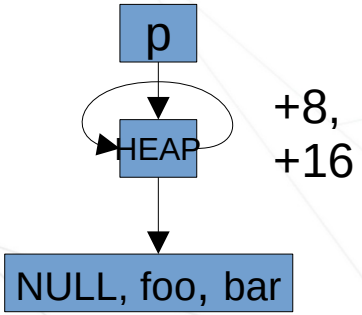
Cast-Unaware

```
struct s  { long *a; long *b; long *c;};

struct s *p = malloc (sizeof(struct s));
                                  //  p +  0 ⊇ HEAP


p->a= NULL;                       // *p +  0 ⊇ NULL
p->b= &foo;                       // *p +  8 ⊇ foo
p->c= cond ? &foo : &bar;         // *p + 16 ⊇ foo
                                  // *p + 16 ⊇ bar


// What does p->b points-to?
```



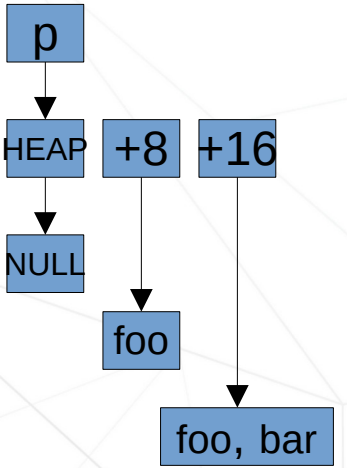
Cast-Aware

```
struct s  { long *a; long *b; long *c;};

struct s *p = malloc (sizeof(struct s));
                                  //  p +  0 ⊇ HEAP


p->a= NULL;                       // *p +  0 ⊇ NULL
p->b= &foo;                       // *p +  8 ⊇ foo
p->c= cond ? &foo : &bar;         // *p + 16 ⊇ foo
                                  // *p + 16 ⊇ bar


// What does p->b points-to?
```



VS

VS

```
struct s  { long a; long b; long c;};
```

VS

```
struct s  { long a; long b; long c;};

struct s r1;
struct s r2;
```

VS

```
struct s  { long a; long b; long c;};

struct s r1;
struct s r2;

r1.a = argc;
r2.b = argc;
```

VS

```
struct s  { long a; long b; long c;};

struct s r1;
struct s r2;

r1.a = argc;
r2.b = argc;

printf(“%ld\n”, r1.a * r2.b);
```

VS

```
struct s  { long a; long b; long c;};

struct s r1; // delete fields (b & c) or c?
struct s r2; // delete fields (a & c) or c?

r1.a = argc;
r2.b = argc;

printf(“%ld\n”, r1.a * r2.b);
```

Interface

```
souffle::SouffleProgram *prog = souffle::ProgramFactory::newInstance("points_to");

souffle::Relation *var = prog->getRelation ("Variable");
souffle::Relation *constraints_rel = prog->getRelation ("RawConstraints");
```

Interface

```
souffle::tuple _tuple (r);
souffle::RamUnsigned _yl(_lhs_t.k1());
souffle::RamUnsigned _el(_lhs_e.k1());
souffle::RamUnsigned _fl(_lhs.k1());
souffle::RamUnsigned _sl(_lhs.k2());
souffle::RamUnsigned _tl(_lhs.k3());
souffle::RamUnsigned _ql(_lhs.k4());
souffle::RamUnsigned _ol(_lhs_o);
souffle::RamUnsigned _yr(_rhs_t.k1());
souffle::RamUnsigned _er(_rhs_e.k1());
souffle::RamUnsigned _fr(_rhs.k1());
souffle::RamUnsigned _sr(_rhs.k2());
souffle::RamUnsigned _tr(_rhs.k3());
souffle::RamUnsigned _qr(_lhs.k4());
souffle::RamUnsigned _or(_rhs_o);
_tuple << _yl << _el << _fl << _sl << _tl << _ql
        << _ol << _yr << _er << _fr << _sr << _tr << _qr << _or;
r->insert (_tuple);
```

Implementation

Pointer/Pointee	Unique Identifier
Global Variable	<G, varpool_node*, x, x, x>
Function	<F, cgraph_node*, x, x, x>
Local Variable	<L, cgraph_node*, id, x, x>
SSA Variable	<S, cgraph_node*, id, x, x>
Abstract Variable	<A, NULL, id, x, x>
String Literal (DECL_INIT)	<C, varpool_node*, x, x, x>
String Literal (gassign)	<C, cgraph_node*, bb_idx, stmt_idx, x>
String Literal (args)	<C, cgraph_node*, bb_idx, stmt_idx, arg_idx>
Heap Variable	<H, cgraph_node*, bb_idx, stmt_idx, x>

Implementation

Expression	Name
A = B	Copy Constraint
A = &B	Address-Of Constraint
A = *B	Scalar-Deref Constraint
*A = B	Deref-Scalar Constraint

Implementation

Expression	Name
A + off_l = B + off_r	Copy Constraint
A + off_l = &B + off_r	Address-Of Constraint
A + off_l = *B + off_r	Scalar-Deref Constraint
*A + off_l = B + off_r	Deref-Scalar Constraint

Implementation

Expression	Name
C + off	Scalar Expression
&C + off	Address-Of Expression
*C + off	Dereference Expression

Implementation

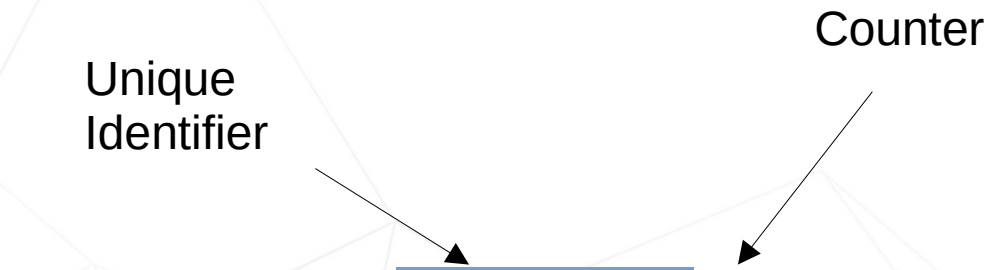
Constraint Record
LHS Expression
LHS Variable Representation
LHS Offset
RHS Expression
RHS Variable Representation
RHS Offset

Soufflé

Unique identifier
(e.g., <G, varpool_node*, x, x, x>

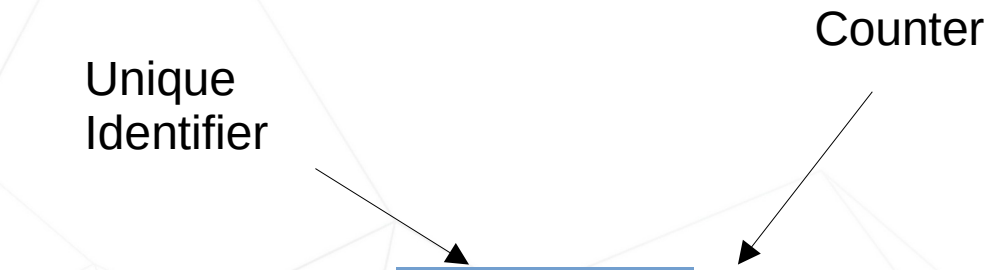
```
.decl Variable (y: v_t, f :f_id, s: s_id, t: t_id, q: q_id)
.input Variable
```

Soufflé



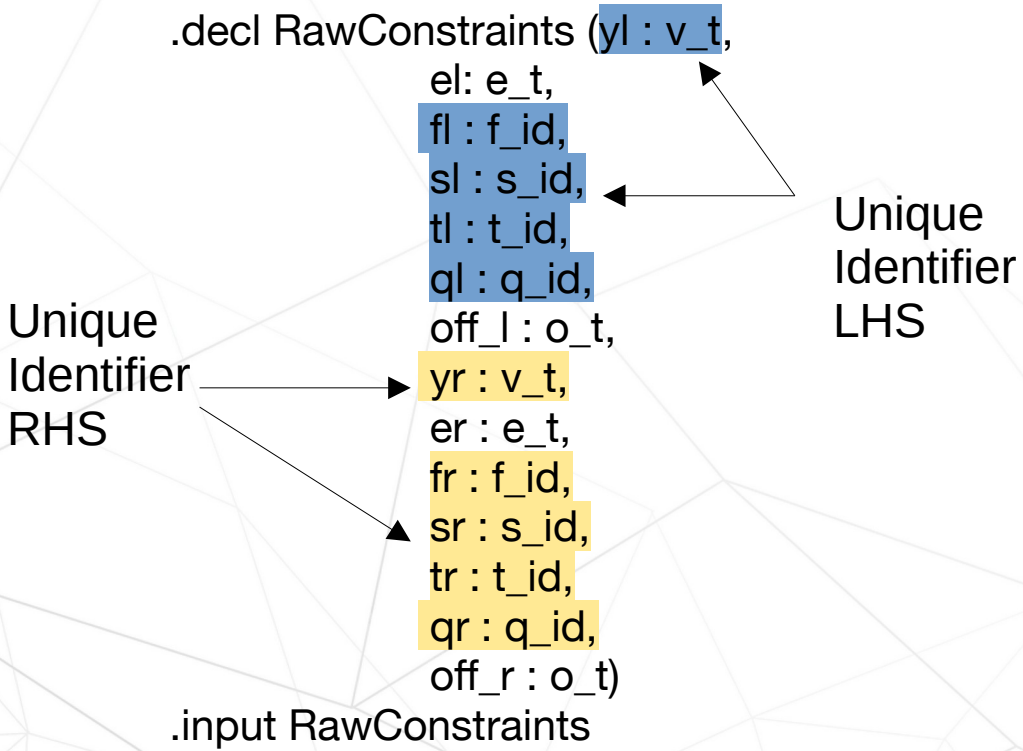

```
VariableMap (y, f, s, t, q, $)
:- Variable (y, f, s, t, q).
```

Soufflé



1. <G, foo, x, x, x>
2. <G, bar, x, x, x>
3. <F, main, x, x, x>

Soufflé


.decl RawConstraints (yl : v_t,
el: e_t,
fl : f_id,
sl : s_id,
tl : t_id,
ql : q_id,
off_l : o_t,
yr : v_t,
er : e_t,
fr : f_id,
sr : s_id,
tr : t_id,
qr : q_id,
off_r : o_t)
.input RawConstraints
Unique Identifier LHS
Unique Identifier RHS

Soufflé

```
.decl RawConstraints (yl : v_t,
                      el: e_t,
                      fl : f_id,
                      sl : s_id,
                      tl : t_id,
                      ql : q_id,
                      off_l : o_t,
                      yr : v_t,
                      er : e_t,
                      fr : f_id,
                      sr : s_id,
                      tr : t_id,
                      qr : q_id,
                      off_r : o_t)
.input RawConstraints
```

Expression Type LHS

Expression Type RHS

Soufflé

```
.decl RawConstraints (yl : v_t,
                      el: e_t,
                      fl : f_id,
                      sl : s_id,
                      tl : t_id,
                      ql : q_id,
                      off_l : o_t,
                      yr : v_t,
                      er : e_t,
                      fr : f_id,
                      sr : s_id,
                      tr : t_id,
                      qr : q_id,
                      off_r : o_t)
.input RawConstraints
```

Offset LHS

Offset RHS

Soufflé

```
Constraints (el, gl, off_l, er, gr, off_r)
  :- RawConstraints (yl, el, fl, sl, tl, ql, off_l, yr, er, fr, sr, tr, qr, off_r)
  , VariableMap (yl, fl, sl, tl, ql, gl)
  , VariableMap (yr, fr, sr, tr, qr, gr)
```

```
SELECT gl
WHERE unique_id = <yl, fl, sl, tl, ql>
FROM VariableMap
```

Soufflé

```
Constraints (el, gl, off_l, er, gr, off_r)
  :- RawConstraints (yl, el, fl, sl, tl, ql, off_l, yr, er, fr, sr, tr, qr, off_r)
  , VariableMap (yl, fl, sl, tl, ql, gl)
  , VariableMap (yr, fr, sr, tr, qr, gr)
```

```
SELECT gr
WHERE unique_id = <yr, fr, sr, tr, qr>
FROM VariableMap
```

Soufflé

```
Constraints (el, gl, off_l, er, gr, off_r)
  :- RawConstraints (yl, el, fl, sl, tl, ql, off_l, yr, er, fr, sr, tr, qr, off_r)
  , VariableMap (yl, fl, sl, tl, ql, gl)
  , VariableMap (yr, fr, sr, tr, qr, gr)
```

Soufflé

```
Constraints (el, gl, off_l, er, gr, off_r)
  :- RawConstraints (yl, el, fl, sl, tl, ql, off_l, yr, er, fr, sr, tr, qr, off_r)
  , VariableMap (yl, fl, sl, tl, ql, gl)
  , VariableMap (yr, fr, sr, tr, qr, gr)
```

```
el gl + off_l = er gr + off_r
PLAIN gl + off_l = ADDRESS_OF gr + off_r
A + 0 = &B + 0
```

Soufflé

PP (gl, off_l, gr, off_r) :- Constraints (e_type_plain, gl, off_l, e_type_plain, gr, off_r).

PA (gl, off_l, gr, off_r) :- Constraints (e_type_plain, gl, off_l, e_type_addressof, gr, off_r).

PS (gl, off_l, gr, off_r) :- Constraints (e_type_plain, gl, off_l, e_type_star, gr, off_r).

SP (gl, off_l, gr, off_r) :- Constraints (e_type_star, gl, off_l, e_type_plain, gr, off_r).

SA (gl, off_l, gr, off_r) :- Constraints (e_type_star, gl, off_l, e_type_addressof, gr, off_r).

SS (gl, off_l, gr, off_r) :- Constraints (e_type_star, gl, off_l, e_type_star, gr, off_r).

Soufflé

PP (gl, off_l, gr, off_r) // A + 0 = B + 0

PA (gl, off_l, gr, off_r) // A + 0 = &B + 0

PS (gl, off_l, gr, off_r) // A + 0 = *B + 0

SP (gl, off_l, gr, off_r) // *A + 0 = B + 0

SA (gl, off_l, gr, off_r) // *A + 0 = &B + 0

SS (gl, off_l, gr, off_r) // *A + 0 = *B + 0

Soufflé

```
PointsTo (pointer, pointee) :- PA (pointer, _, pointee, _).

PointsTo (pointer, pointee) :- PP (pointer, _, temp, _)
  , PointsTo (temp, pointee).

PP (left, 0, right, 0) :- PS (left, _, temp, _)
  , PointsTo (temp, right).

PP (left, 0, right, 0) :- SP (temp, _, right, _)
  , PointsTo (temp, left).

PA (left, 0, pointee, 0) :- SA (temp, _, pointee, _)
  , PointsTo (temp, left).

PS (left, 0, right, 0) :- SS (temp, _, right, _)
  , PointsTo (temp, left).
```

Soufflé

```
PointsToFeedback (yl, fl, sl, tl, ql, yr, fr, sr, tr, qr) :- PointsTo (gl, gr)
 , VariableMap (yl, fl, sl, tl, ql, gl)
 , VariableMap (yr, fr, sr, tr, qr, gr)
 .
```

```
SELECT unique_id = <yl, fl, sl, tl, ql>
WHERE gl
FROM VariableMap
```

```
SELECT unique_id = <yr, fr, sr, tr, qr>
WHERE gr
FROM VariableMap
```

Bibliography

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