Precise and Compact Modular Procedure Summaries for Heap Manipulating Programs

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Goal:

Perform a precise flow- and context- sensitive pointer analysis that is modular and bottom-up

Advantages of Modular Pointer Analysis

- Reuse of results: Same summary can be reused in any context

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  - $\Rightarrow$ Each function only analyzed once (assuming no cycles)
- Scalability: Summaries express only externally visible side effects
  - $\Rightarrow$ Allows local reasoning
- Natural parallelization: Functions that do not have caller-callee relationship can be independently analyzed

Unfortunately performing a modular pointer analysis is difficult!

$\Rightarrow$ particularly if we want to perform strong updates to memory locations!

Motivating Example

```
f(int** a, int **b,
  int *p, int *q)
{
  *a = p;
  *b = q;
  **a = 3;
  **b = 4;
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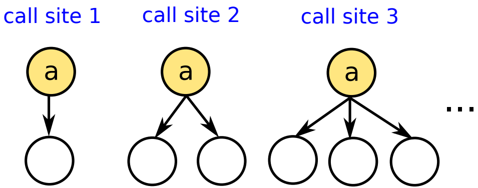
- Although `f` is conditional and loop-free, it may have very different effects at different call sites
- Example: After a call to `f`, value of `*p` may be 3, 4, or remain its initial value

  ... depending on points-to facts at call site!

Two Main Difficulties

One difficulty: An argument `a` to a function `f` may have different number of points-to targets at different call sites of `f`



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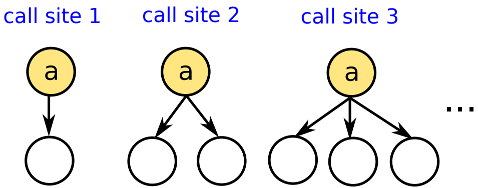

⇒ Unknown number of points-to targets at call sites

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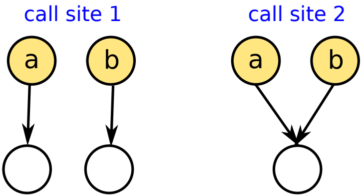
Another difficulty: Different aliasing patterns between arguments may exist at different call sites



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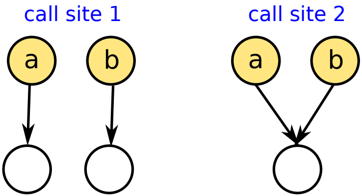

⇒ Aliasing patterns exponential in number of locations

Overview of Our Approach

- Represent unknown points-to targets of locations using location variables

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- To allow strong updates, ensure that locations represented by two distinct variables stand for disjoint set of locations
- Enforce disjointness by symbolically representing all possible aliasing relations on function entry

Location Constants vs. Variables

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- Location Constants: Model memory allocations, NULL, locations of stack variables etc.
- Location Variables: Range over the unknown location constants pointed to by arguments at function entry

Simple Example

foo(int* a)

ν ranges over abstract memory locations at call sites of foo

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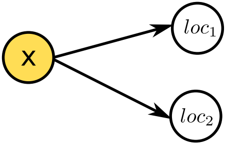
foo(int* a)

...
foo(x)
...



ν ranges over abstract memory locations at call sites of foo

In this context, ν stands for location constants loc_1 and loc_2

If ν_1 and ν_2 are two distinct location variables in `f`, we can only apply strong updates to them in `f` if:

$$\gamma(\nu_1) \cap \gamma(\nu_2) = \emptyset$$

in any calling context

Strong Updates to Location Variables

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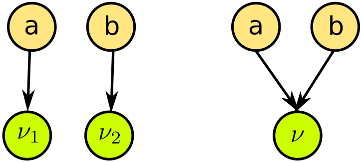
Why?

If ν_1 and ν_2 may represent an overlapping set of locations, updates to ν_1 may affect updates to ν_2

Enforcing Disjointness: Naive Solution

- If arguments `a` and `b` are potential aliases, analyze function in two different initial configurations:



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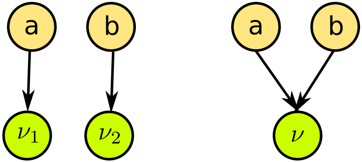

Problem:

Number of alias patterns = nth Bell number
(n= # of argument-reachable locations)

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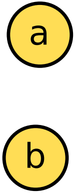
- Only need to analyze each function once

$\Rightarrow$ Since we precisely account for all aliasing patterns in any context, it is safe to apply strong updates to (non-summary) location variables

Construction of the Initial Points-to Graph

Consider function: `foo(int* a, int* b)`



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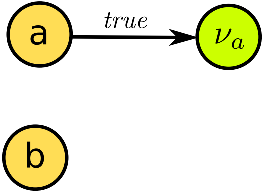

ν_a represents points-to targets of `a` in any calling context

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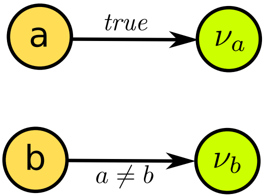

ν_b represents points-to targets of b only in those contexts where a and b do not alias

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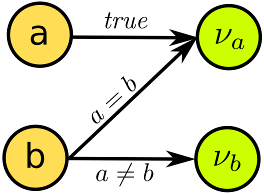

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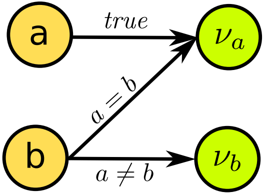

ν_a also represents points-to targets of `b` in those contexts where `a` and `b` alias

Observe: Construction enforces that $\gamma(\nu_a) \cap \gamma(\nu_b) = \emptyset$

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- Consider variables $a_1, \ldots, a_n$ that may alias at function entry

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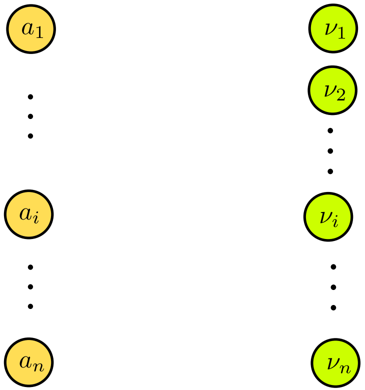

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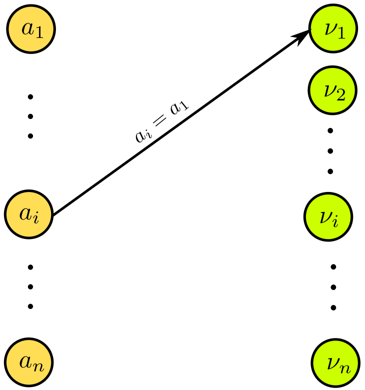

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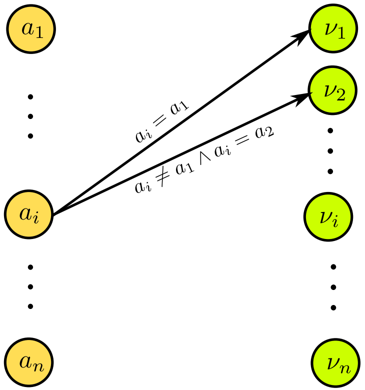

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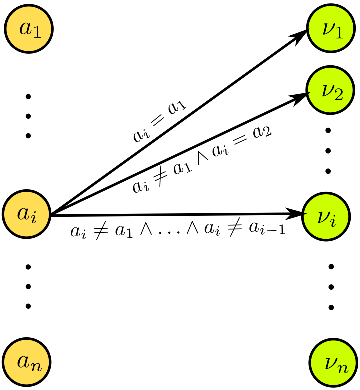
- Impose total order such that $a_1 < a_2 \ldots < a_n$
- For each a_i introduce ν_i
- Each a_i points to ν_k with $k \leq i$ under constraint:

$$\bigwedge_{j<k} a_i \neq a_j \;\wedge\; a_i = a_k$$



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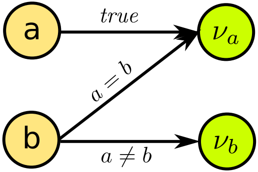

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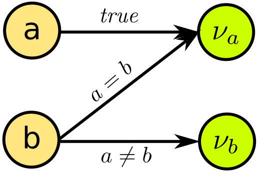

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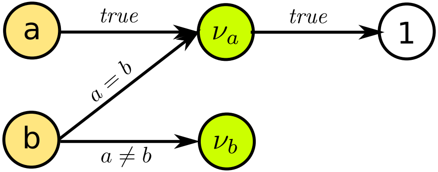

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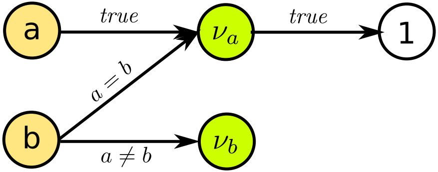

Observe: `*b` has value 1 if `a` and `b` alias

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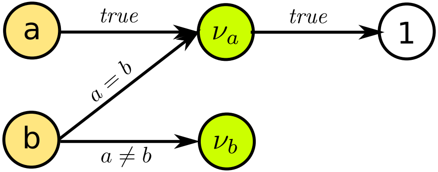

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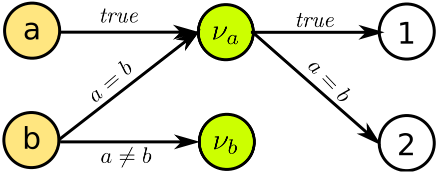

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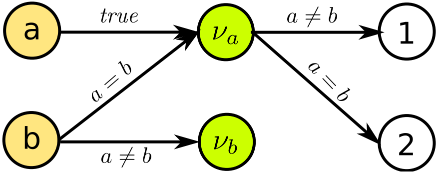

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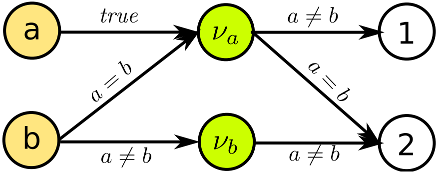

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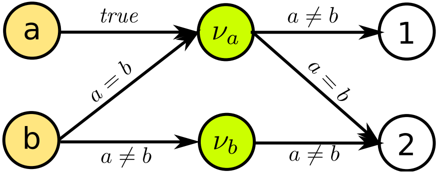

Observe: `*a` has value 1 if `a` and `b` do not alias and value 2 otherwise

Experiments

- Analyzed 4 large open-source C and C++ applications:
  - OpenSSH
  - LiteSQL
  - Inkscape Widgets
  - DigiKam

First Experiment

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- Checked for various memory safety properties, such as buffer overruns, null dereferences, accessing deleted memory, ...
- Compared false positive rates of new analysis with analysis that only performs weak updates at call sites

Comparison of False Positives

- Weak updates at call sites:
  98.2% false positive rate

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⇒ Modular analysis that cannot apply strong updates too imprecise!

Comparison of Running Times

- Weak updates at call sites: 20.0 min average running time on single CPU

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⇒ More precise actually analysis runs faster

Analysis can be parallelized

- Also ran this analysis on 8 CPUs

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- Functions with no caller-callee relationship analyzed in parallel

Analysis can be parallelized

- Also ran this analysis on 8 CPUs
- Functions with no caller-callee relationship analyzed in parallel
- Average speed-up over 1 CPU: $4.2\times$ speedup

Second Experiment

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- Explored growth of heap summaries vs. depth of call chain

Second Experiment

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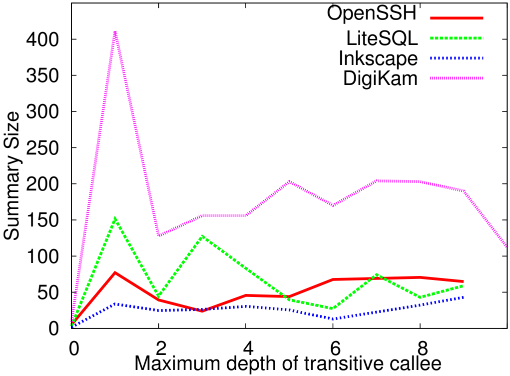
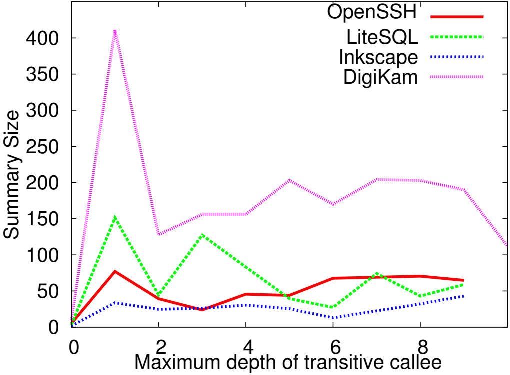
- Explored growth of heap summaries vs. depth of call chain
- Measured summary size as the number of points-to edges weighted according to the size of the edge constraints

Results


OpenSSH
LiteSQL
Inkscape
DigiKam
Summary Size
0
50
100
150
200
250
300
350
400
0
2
4
6
8
Maximum depth of transitive callee

Results



Local reasoning by focusing only on externally-visible side effects

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- Demonstrated practicality of technique for verifying memory safety on four applications

Thanks!

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