CFA2: a Context-Free Approach to Control-Flow Analysis

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What is a flow analysis?

Flow analysis: find information about the control and data flow of a program without running it.

Applications

Bug finding

argument mismatch
type mismatch
array-index out of bounds
dead-code detection

Semantic navigation

what functions get called at this call site
what flows to this variable

Optimization

classic dataflow optimizations
function-call resolution
type recovery for tag elimination

From graphs to pushdown models

Program as a graph whose nodes are the program points.
$\Rightarrow$ executions are strings in a regular language.
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Fine for conditionals and loops (think Fortran).
Weak for first-class functions.

Approximate program with pushdown automaton.
$\Rightarrow$ unbounded call/return matching.

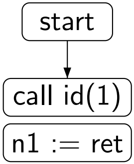
```
(define id (λ(x) x))

(let* ((n1 (id 1))
       (n2 (id 2)))
  (+ n1 n2))
```

0CFA execution

start

Global environment:

0CFA execution



Global environment:

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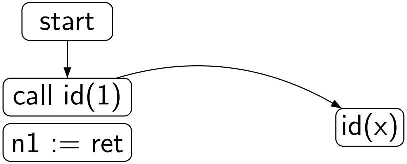

Global environment:

x	1

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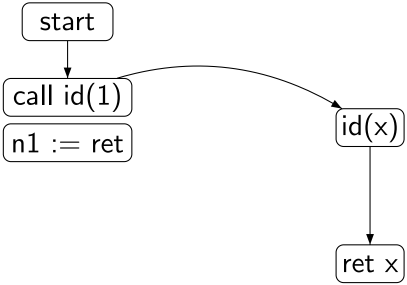

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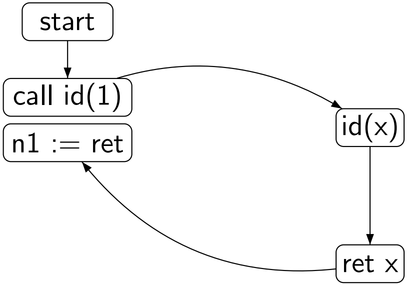

Global environment:

x	1
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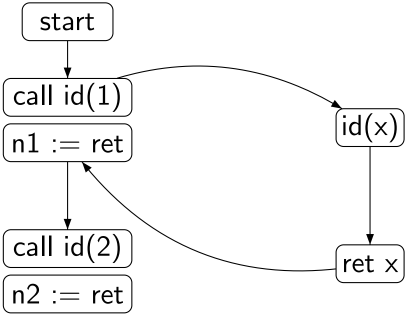

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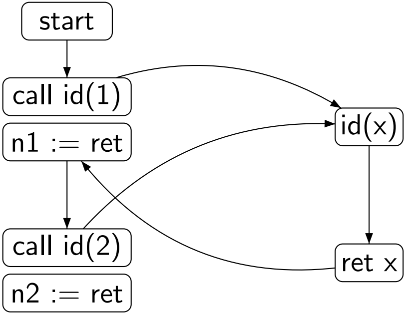
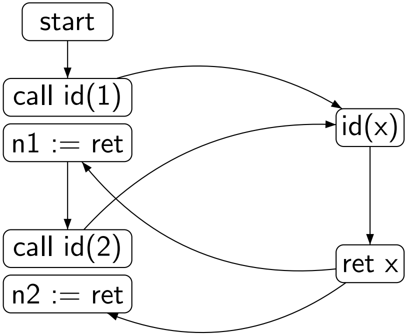


Global environment:

x	1	2
n1	1	

0CFA execution



Global environment:

x	1	2
n1	1	2
n2	1	2

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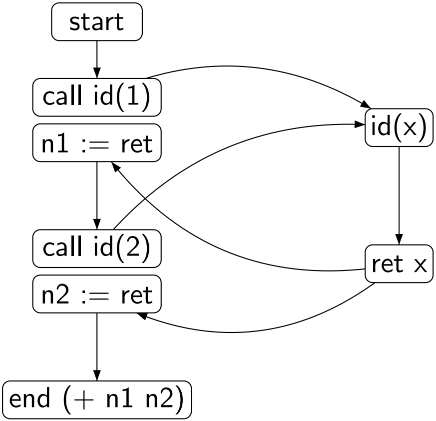

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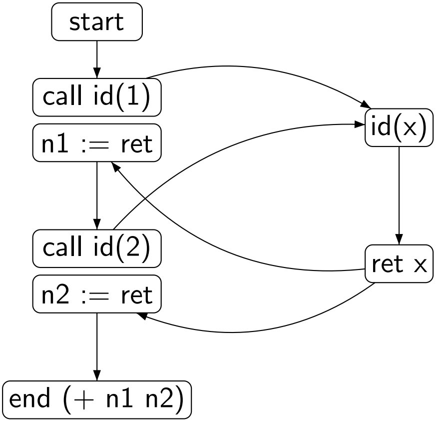

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Call/return mismatch causes spurious flows
⇒ commonly called functions pollute the analysis.

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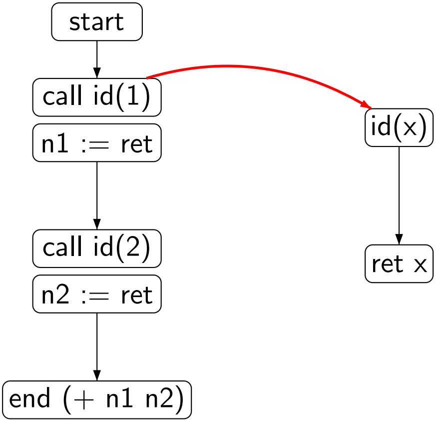

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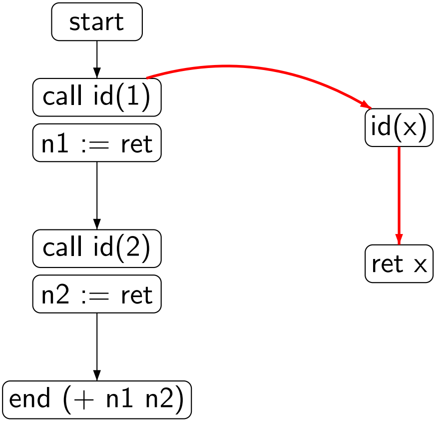

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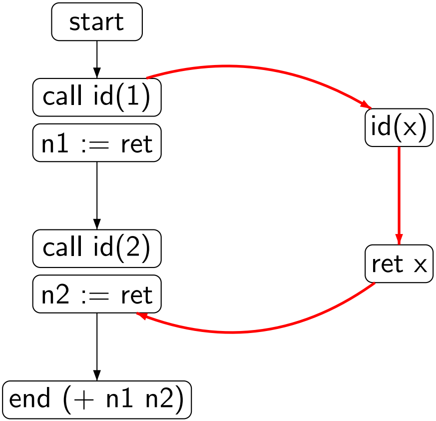

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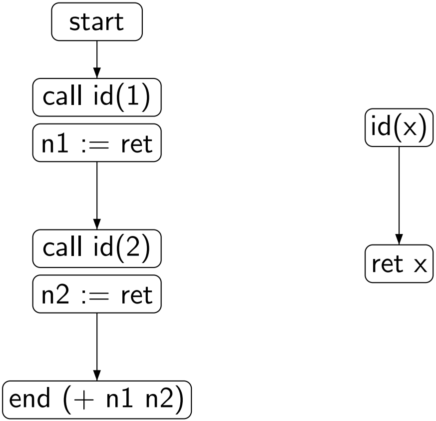

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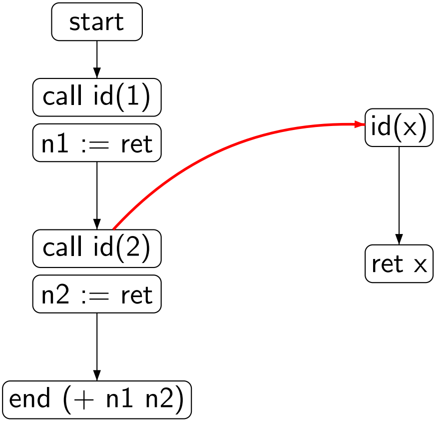

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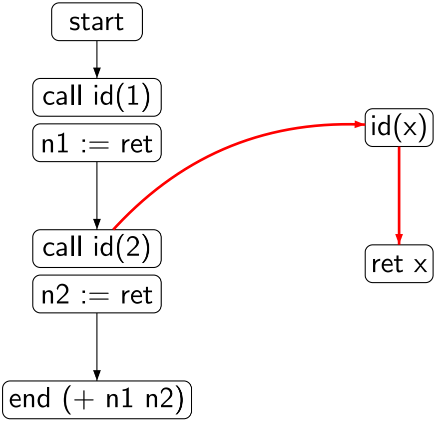

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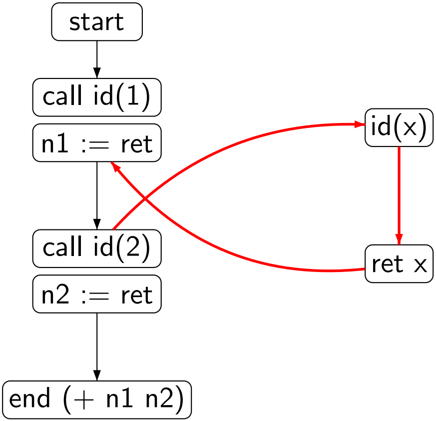

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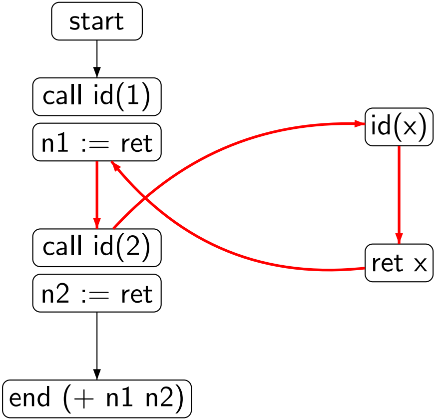

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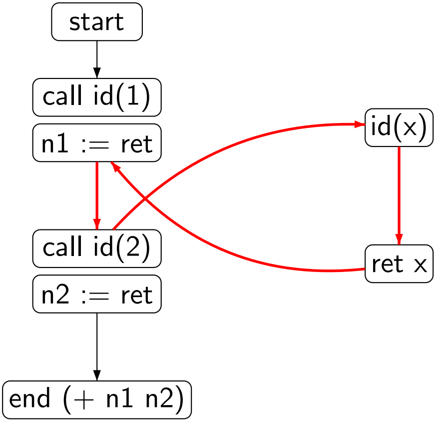

Global environment:

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Can't use a graph model to calculate stack change
⇒ stack-based optimizations out of reach.

Fake Rebinding

```
(define (compose-same f x)
  ^2(f ^1(f x)))
```

Fake Rebinding

(define (compose-same f x) λ_a λ_b

^{2}(f ^{1}(f x)))

Fake Rebinding

`(define (compose-same f x)` λ_a λ_b

^{2}`(f` ^{1}`(f x)))`

Flows:

^{2}`(f` ^{1}`(f x))`

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(define (compose-same f x)                 λa          λb
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Fake Rebinding

`(define (compose-same f x)` λ_a λ_b

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Flows:

^{2}`(`λ_a ^{1}`(`λ_a `x))` ✓

Fake Rebinding

`(define (compose-same f x)` λ_a λ_b

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Flows:

$^{2}(\lambda_a\ ^{1}(\lambda_a$ `x))` ✓

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λ_a λ_b

Flows:

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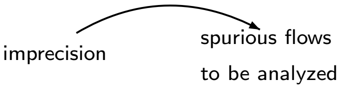
The vicious cycle of approximation



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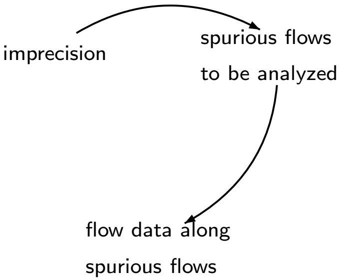

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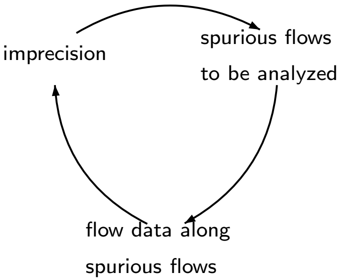

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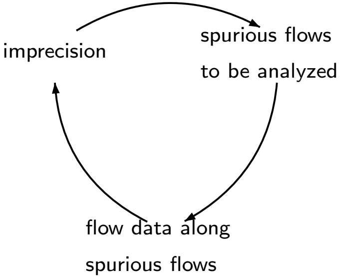

- In HOFA, imprecision can increase running time.
- *k*-CFA intractably slow for $k > 0$ (Van Horn–Mairson).

CFA2: pushdown automaton

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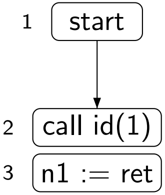
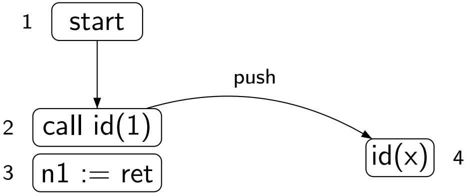


Stack:

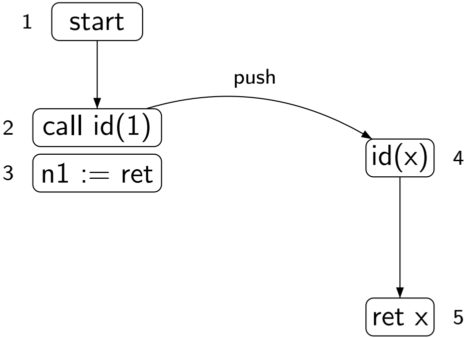
CFA2: pushdown automaton



Stack:

| x ↦ 1, ret ↦ 3 |

CFA2: pushdown automaton



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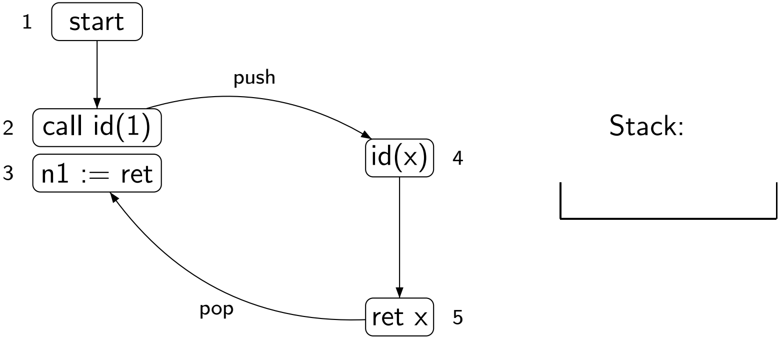

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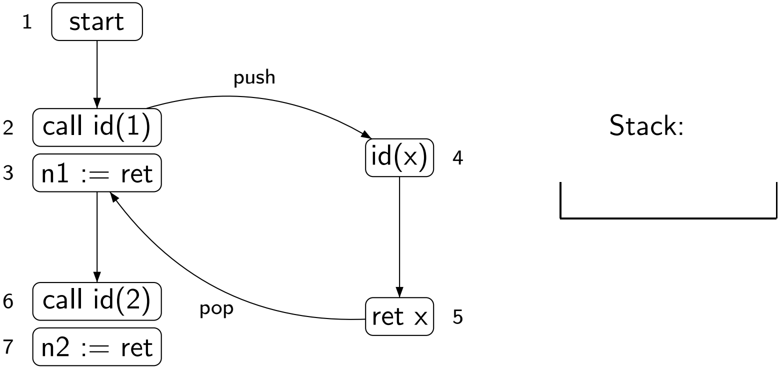

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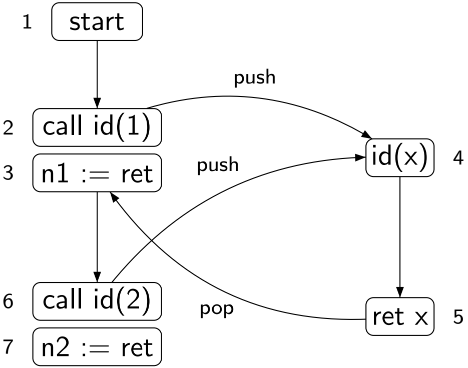
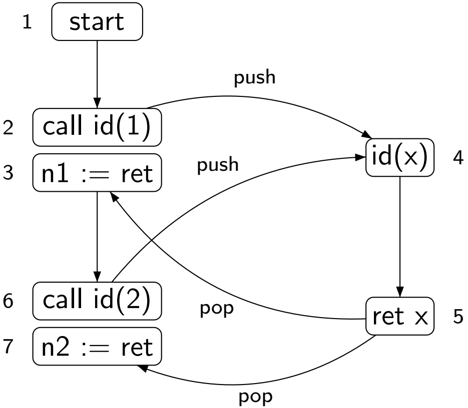


Stack:

$x \mapsto 2$, $ret \mapsto 7$

CFA2: pushdown automaton



Stack:

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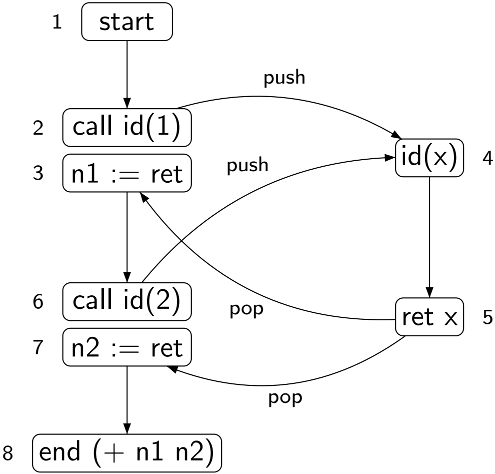

Stack:

Summarization

Why:

Stack can grow arbitrarily—infinite state space
$\Rightarrow$ simple analysis techniques won't terminate!

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Summarization handles infinite-space issue (Sharir–Pnueli, Reps).

How:

On function entry, forget return point; remember before return.

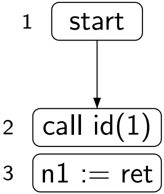
Inside a function, remember only the top frame.

To avoid reanalyzing functions often, record summaries from function entries to function exits.

CFA2: summarization

1 start

CFA2: summarization



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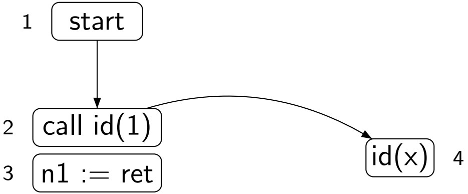
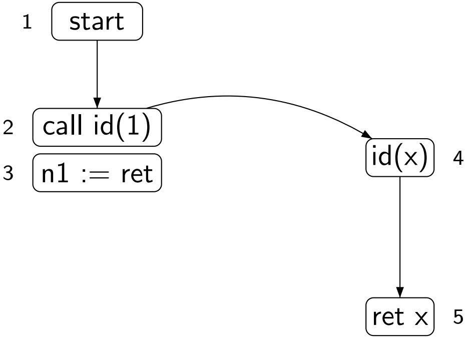


Callers:
2 calls 4[x $\mapsto$ 1]

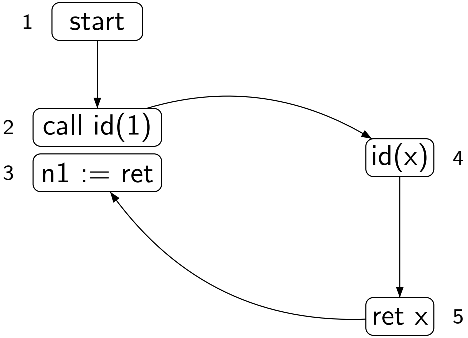
CFA2: summarization



Callers:
2 calls 4[x $\mapsto$ 1]

Summaries:
4[x $\mapsto$ 1] goes to 5[x $\mapsto$ 1]

CFA2: summarization



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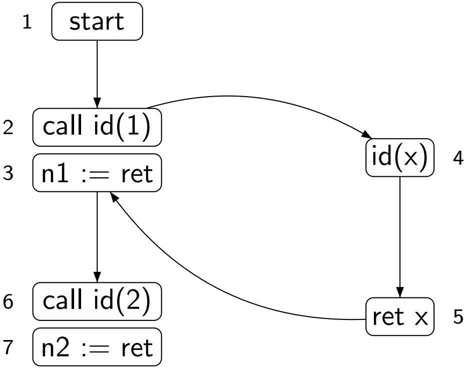
Toplevel:
n1 1

CFA2: summarization



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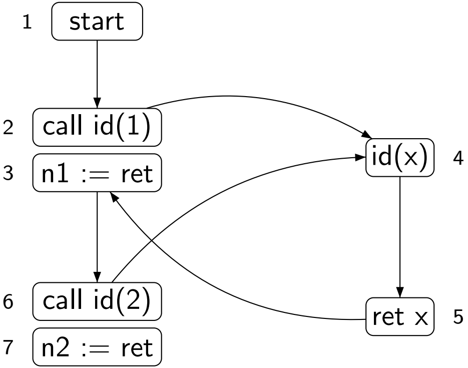
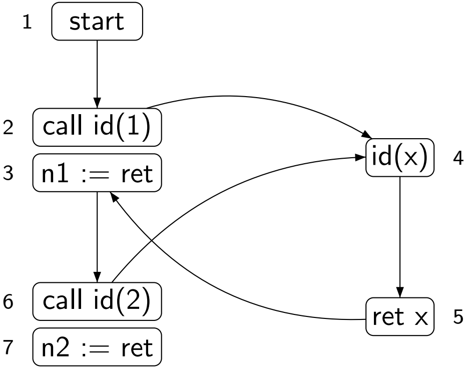


Callers:
2 calls 4[x $\mapsto$ 1]
6 calls 4[x $\mapsto$ 2]

Summaries:
4[x $\mapsto$ 1] goes to 5[x $\mapsto$ 1]

Toplevel:
n1 1

CFA2: summarization



Callers:
2 calls 4[x $\mapsto$ 1]
6 calls 4[x $\mapsto$ 2]

Summaries:
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Toplevel:
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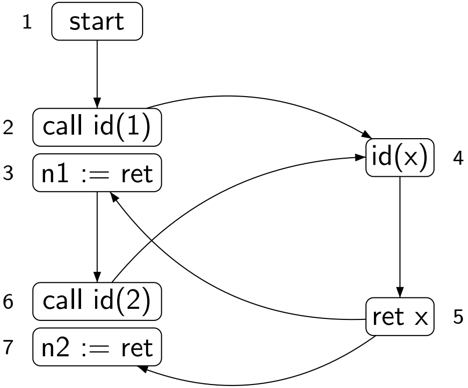

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Toplevel:

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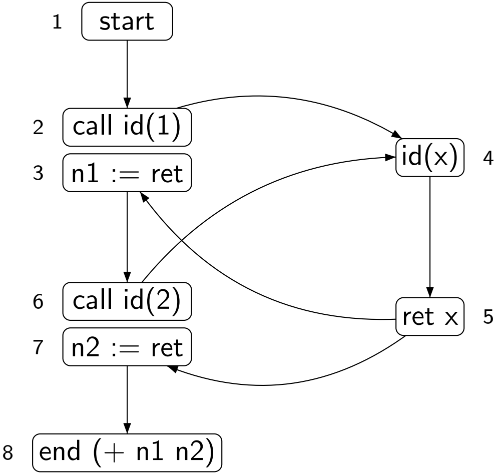

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Stack filtering

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λ_a λ_b

Flows:	Frame:	Action:
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`²(f ¹(f x))`	$[\mathrm{f} \mapsto \{\lambda_a, \lambda_b\}]$	pick a lambda
`²(f ¹(`λ_a` x))`	$[\mathrm{f} \mapsto \{\lambda_a\}]$	commit to λ_a

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^{2}(f ^{1}(λ_a x))	$[\mathsf{f} \mapsto \{\lambda_a\}]$	commit to λ_a
^{2}(λ_a ^{1}(λ_a x))	$[\mathsf{f} \mapsto \{\lambda_a\}]$	

Stack filtering

`(define (compose-same f x)` λ_a λ_b

^{2}`(f` ^{1}`(f x)))`

Flows:	Frame:	Action:
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^{2}(λ_a ^{1}(λ_a x))	$[\mathsf{f} \mapsto \{\lambda_a\}]$	

Similarly for λ_b

Stack and heap references

Stack filtering possible because both references to f in top frame (stack references).

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Some references not in top frame though (heap references), e.g., `(λ(x)(λ(y) (+ x y)))`

Characteristics of CFA2

- handles first-class functions, tail calls.
- unbounded call/return matching.
- applies to statically typed and dynamic languages.
- precise lookup for stack references.
- strong update for stack references.

Correctness

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Soundness

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Completeness

. . . and it doesn't add spurious flows.

Benchmarks

	$S_?$	$H_?$	0CFA		1CFA		CFA2	
			visited	const	visited	const	visited	const
`len`	9	0	81	0	126	0	55	2
`rev-iter`	17	0	121	0	198	0	82	4
`len-Y`	15	4	199	0	356	0	131	2
`tree-count`	33	0	293	2	2856	6	183	10
`ins-sort`	33	5	509	0	1597	0	600	4
`DFS`	94	11	1337	8	6890	8	1709	16
`flatten`	37	0	1520	0	6865	0	478	5
`sets`	90	3	3915	0	54414	0	4233	4
`church-nums`	46	23	19130	0	19411	0	24580	0

Future work

- `call/cc`
- increase precision in heap (Might–Shivers ΓCFA).
- escape analysis: stack allocation of closures, cons cells etc.

Conclusions

- Flow-analysis of higher-order languages has captivated researchers for the past 20 years.
- CFA2 models well the important control-flow structure of these languages: function call/return.
- Exciting possibilities opening up:
  - optimization
  - informative development environments
  - compile-time error detection

Thank you!