Fast Liveness Checking for SSA-Form Programs

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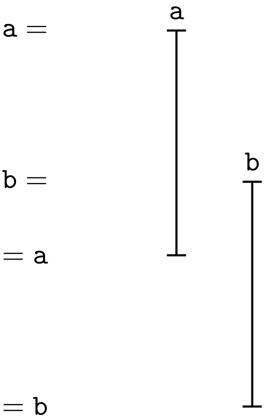
Outline

Outline

Why do we need liveness analysis?

Resources analysis

- Scheduling
- Coalescing/Register-allocation
- PRE sensitive to register pressure



Two approaches

Classical Approach: Liveness Sets (LS)

For *every* block boundary, the set of *all* live variables

- Expensive precomputation (space & time), fast query
- Usually, not all computed information is needed
- Adding, (re-)moving instructions ⇒ recompute information

Our Approach: Liveness Checking (LC)

Answer *on demand:* Is variable live at program point?

- Faster precomputation, slower queries
- Information depends only on CFG and def-use chains
- Information invariant to adding, (re-) moving instructions

Outline

Foundations

- Control Flow Graph
- SSA with dominance property

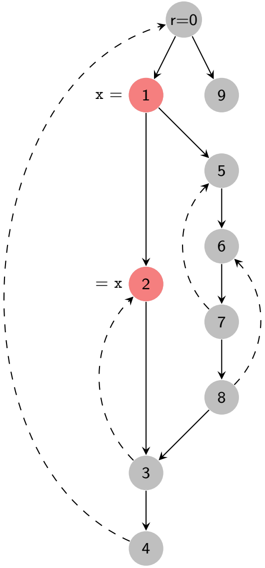
Liveness

Concept

- Defined in the past: reaching definition
- Used in the future: upward exposed use

Definition (live-in)

A variable a is live-in at a node q if there exists a path from q to a node u where a is used and that path does not contain its definition d



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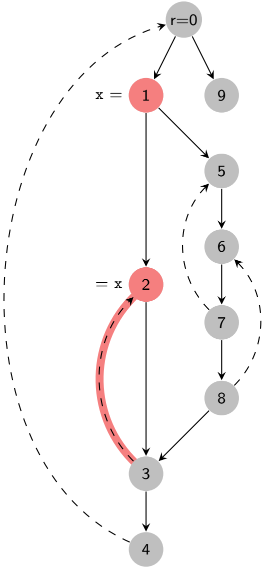

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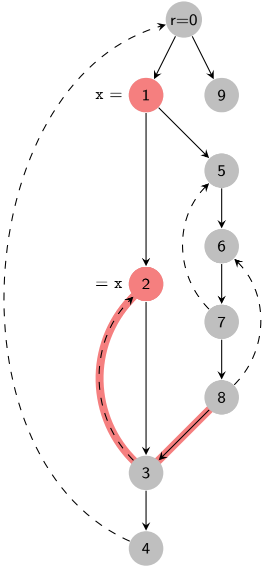

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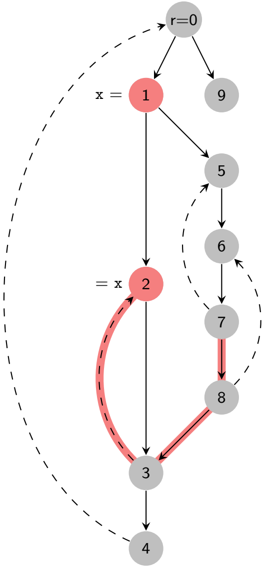

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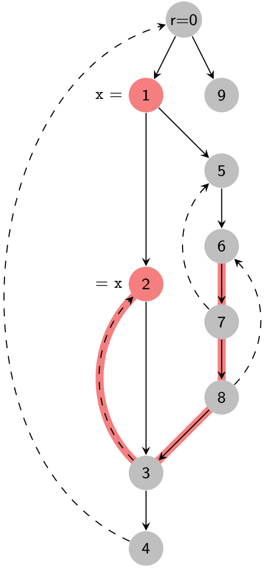

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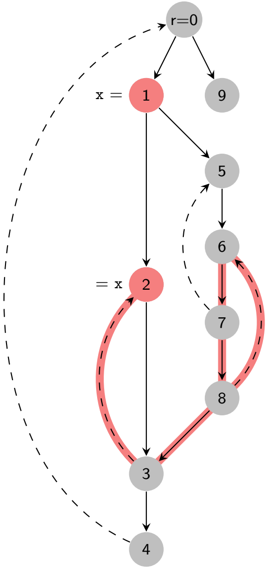

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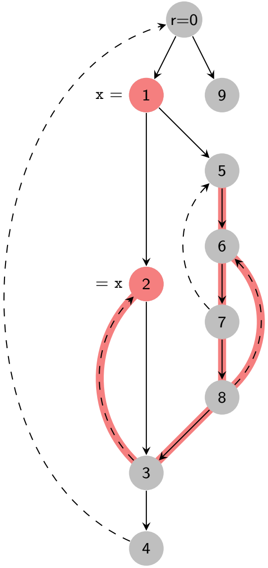

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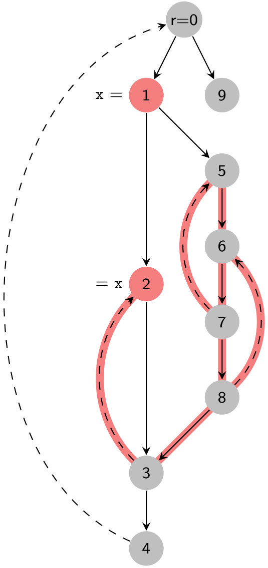

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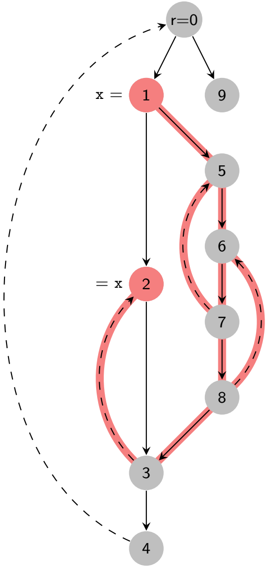

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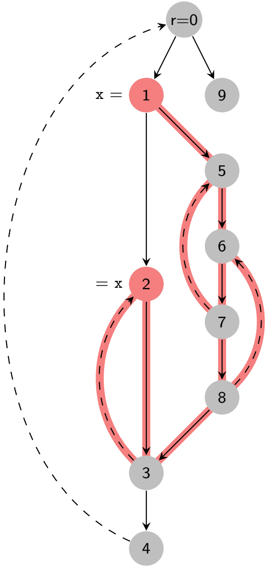

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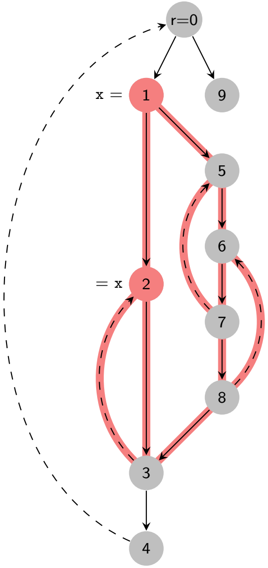

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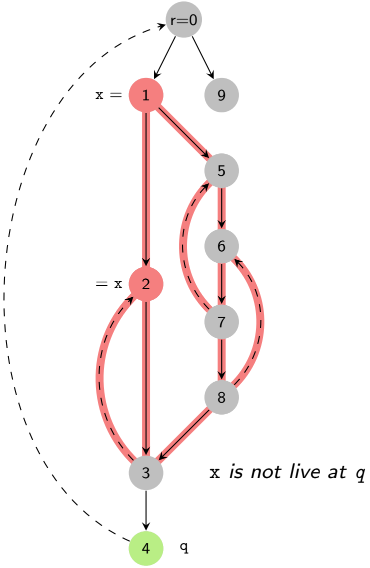

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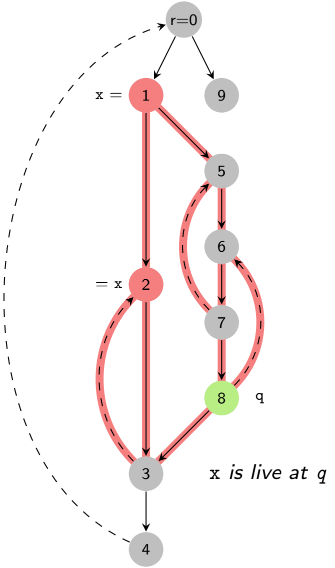
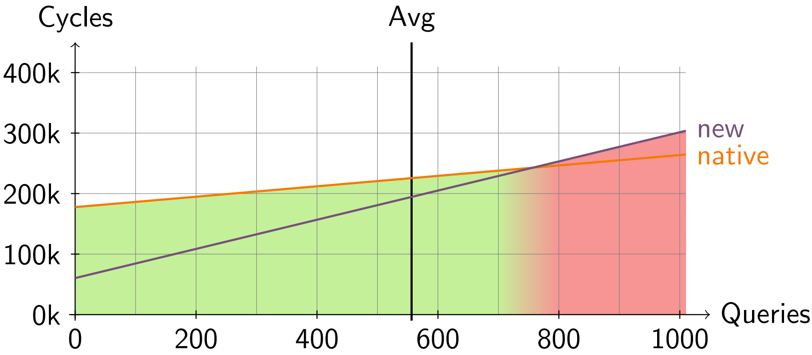


Liveness: precomputation versus queries

- Classical liveness (data-flow):
  - Costly precomputation
  - Almost constant queries
- Our solution:
  - Fast precomputation
  - Queries almost linear in the number of uses



Cycles
Avg
400k
300k
200k
100k
0k
new
native
Queries
0
200
400
600
800
1000

Outline

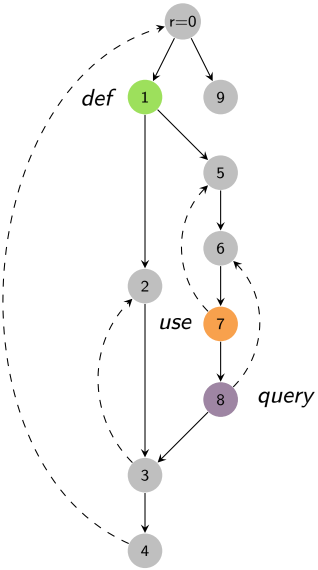
Principle

Goal:
From all the paths from *query* to *use*, remove those going through *def* .

Highest point

Last point of the path such that all the following points are below.

If the highest point is dominated by *def* then the whole path is.



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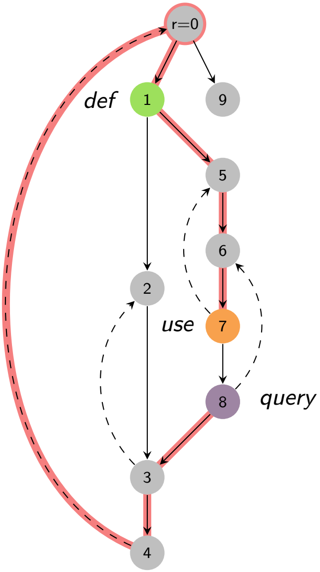

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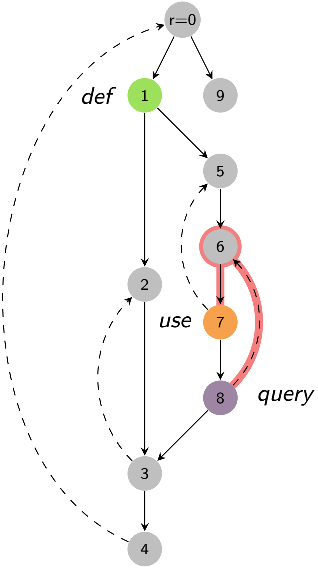

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- For each node *q* of the CFG, compute the set of potential *highest points* of every path starting at *q*.
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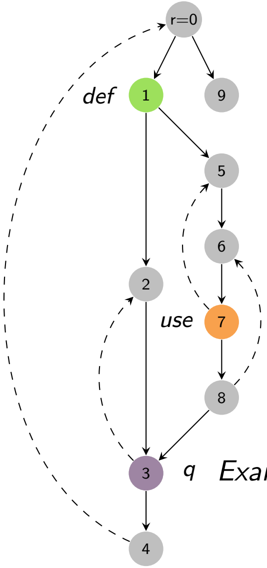

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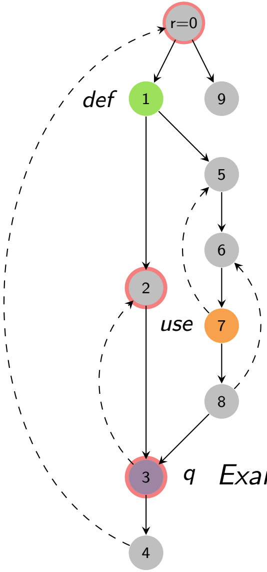

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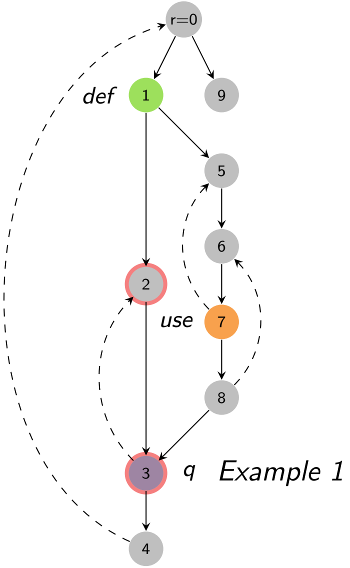

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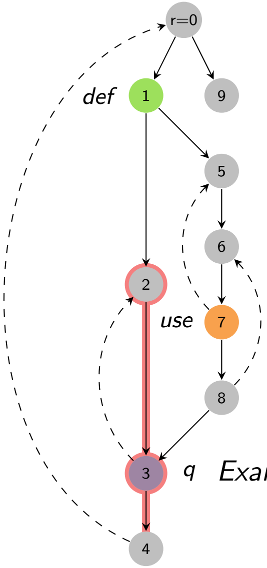

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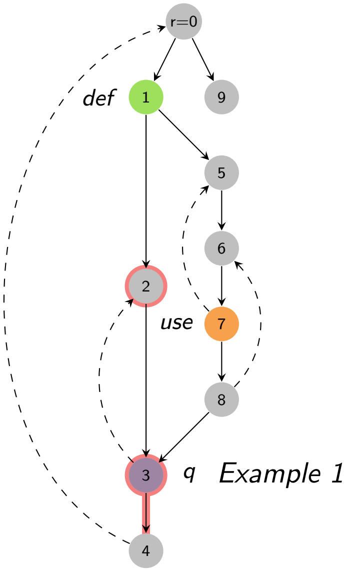

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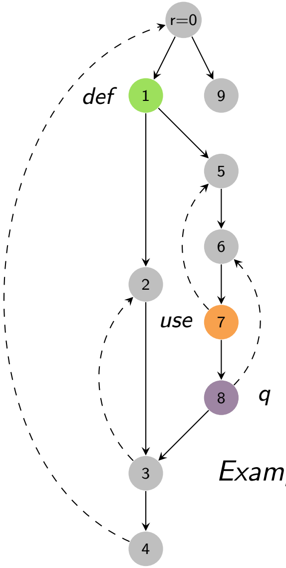

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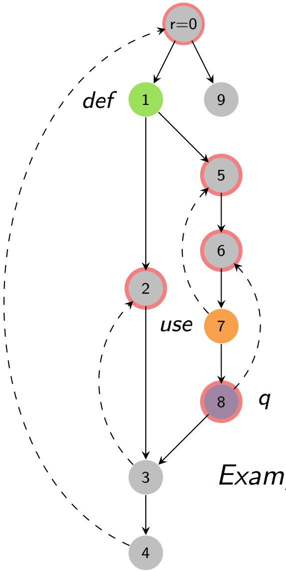

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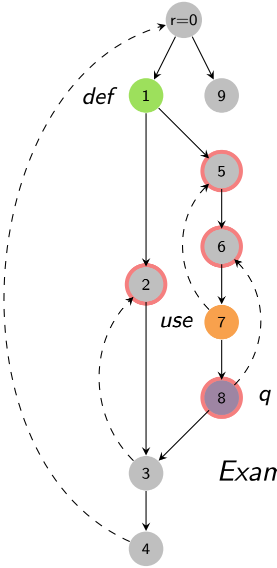

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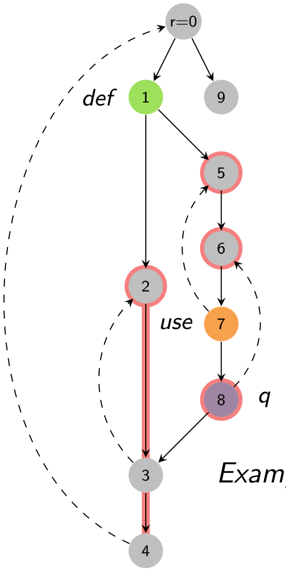

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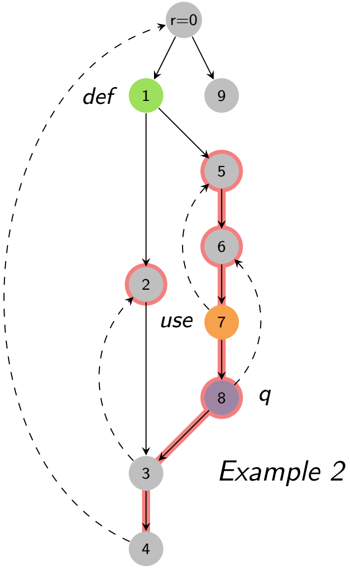

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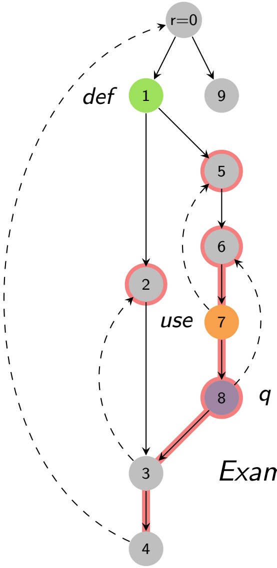

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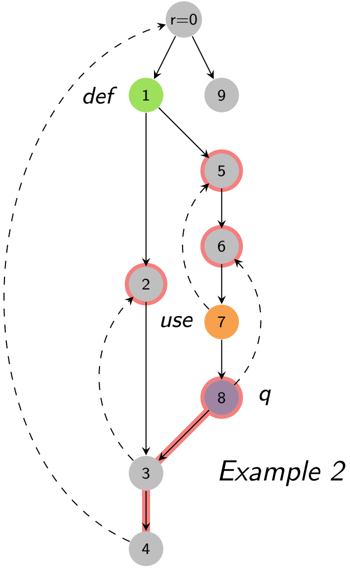


Algorithm

Precomputation

1. Compute transitive closure on the reduced graph G'
   - G' = CFG without DFS back edges (cycle-free)
   - Simple to compute: post-order traversal
2. For each node q compute a set T_q of possible highest points (back-edge targets)
   - Also simple to compute: pre-order and post-order traversal

Query

- For each *use*:
  - For each $t \in T_q$ dominated by *def*:
    - Test reachability in the reduced graph

Implementation Tricks

- Reachability and T_q can be efficiently implemented as bitsets
- For reducible CFGs there is exactly one "highest" back-edge target
  - dominates all the other back-edge targets
  - sufficient to check from there
- Hence, order nodes according to dominance
  ☞ "highest" node is first set bit in T_q

Outline

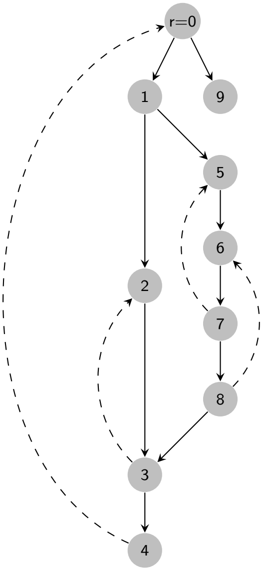
Loop Nesting Forest

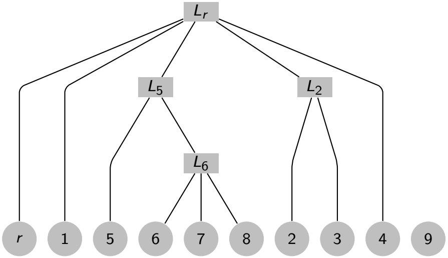
Use the same idea:

- Pre-compute reachability
- Filter path that does not contain d in constant time

Instead of the highest point, use the loop nesting information to filter.

Loop nesting forest: recursive definition using decomposition in Strongly Connected Components (SCC).


r=0
1
9
5
6
2
7
8
3
4


L_r
L_5
L_2
L_6
r
1
5
6
7
8
2
3
4
9

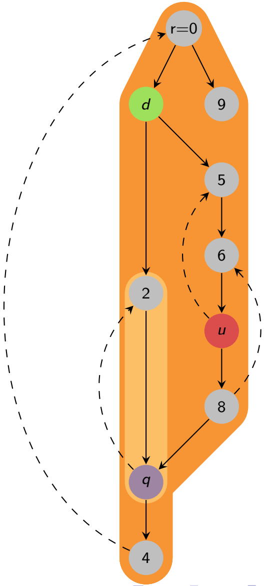
Loop Nesting Forest & Liveness

Theorem (loop-edge free path)

Given d, q, and u such that:

- *d dominates u*
- *d dominates q*

A path from q to u does not contain d iff it does not contain any loop-edge of any loop containing d



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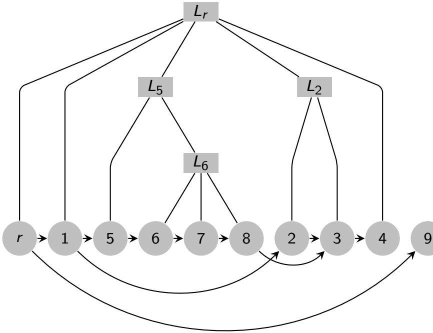
Pre-computation

Compute reachability in the following Directed Acyclic Graph (DAG):

- $G - \{\text{loop-edge}\}$
- replace edge $a \to b$ into edge $a \to h$ (h header of the largest loop containing b not a)

Complexity: $O(\#BB)$ operations on bit-sets



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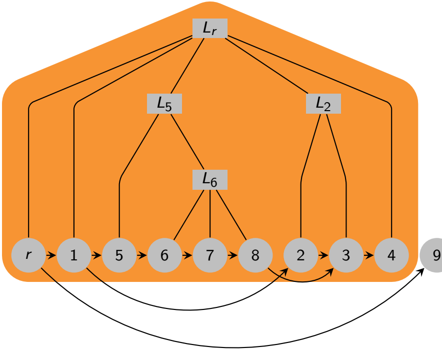

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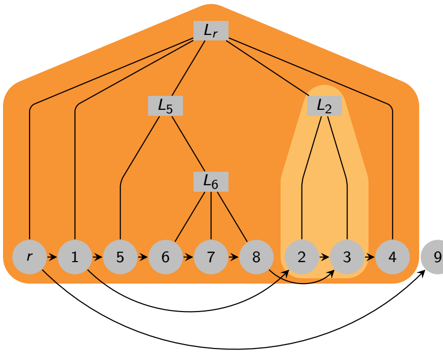

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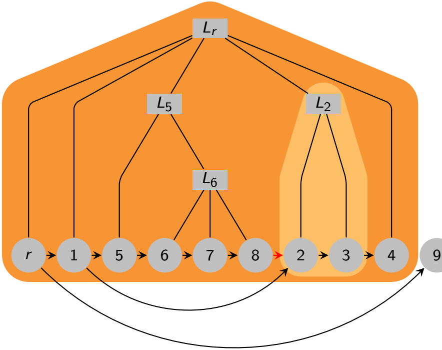

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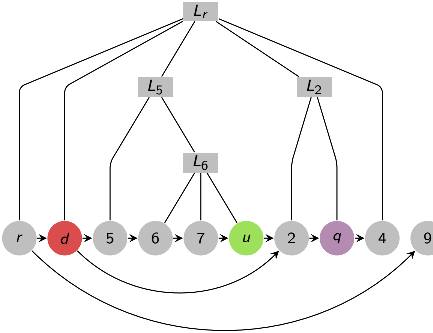
Query ($O(\#uses)$ operations on bit-sets)

For each use u:

- h: the largest loop containing q and not not d
- test if u is reachable from h



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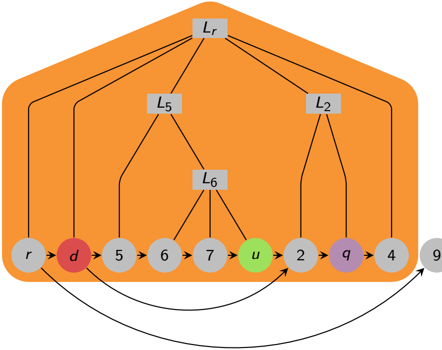

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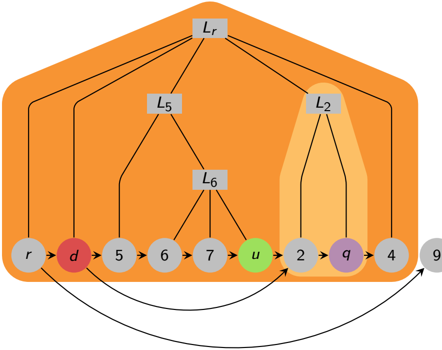

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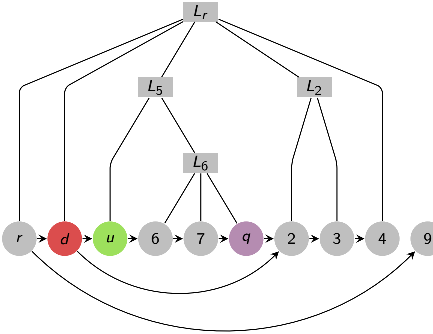

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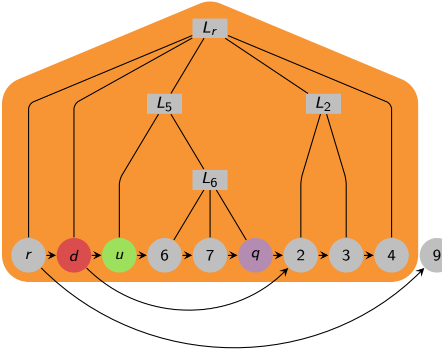

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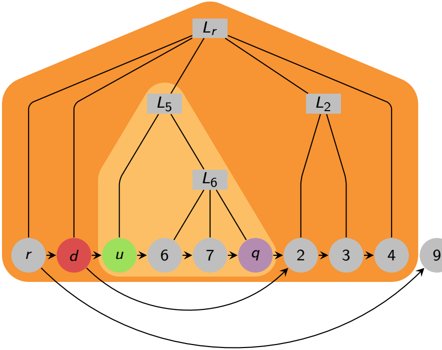

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Evaluation

Setup

- Implemented in LAO, code generator developed by STMicroelectronics
- Benchmarked with a subset of SPEC2000 (CINT)
- Liveness-analysis used during SSA deconstruction

The main factors influencing the speed of our algorithm are:

- the number of uses per variable ($\#uses$)
- the number of basic blocks ($\#BB$)
- the number of CFG edges ($\#edges$)

Quantitative Evaluation

	# of Uses per Variable			
Benchmark	Maximum	$\% \leq 1$	$\% \leq 2$	$\% \leq 3$
164.gzip	51	65.64	86.38	92.81
175.vpr	75	70.36	88.90	93.93
176.gcc	422	73.99	87.81	92.42
181.mcf	46	66.91	83.50	89.33
186.crafty	620	72.98	90.09	93.85
197.parser	96	65.12	86.75	94.26
254.gap	156	70.46	85.95	91.26
255.vortex	254	65.99	90.80	95.02
256.bzip2	36	69.89	89.89	94.47
300.twolf	165	69.71	87.59	93.23
Total	620	71.30	87.85	92.76

Quantitative Evaluation

	# of Basic Blocks		
Benchmark	Average	% $\leq$ 32	% $\leq$ 64
164.gzip	33.35	69.51	85.36
175.vpr	34.45	68.88	84.44
176.gcc	38.96	72.85	86.03
181.mcf	20.31	84.61	100.00
186.crafty	69.28	59.63	76.14
197.parser	23.60	84.82	93.49
254.gap	32.89	67.60	87.44
255.vortex	26.46	77.57	90.68
256.bzip2	22.97	78.37	91.89
300.twolf	56.97	59.47	77.36
Total	35.21	72.71	87.18

Runtime Experiments

	Speedup		
Benchmark	Precomputation	Queries	Both
164.gzip	3.12	0.53	1.16
175.vpr	2.17	0.48	1.41
176.gcc	3.03	0.26	1.00
181.mcf	1.85	0.44	1.39
186.crafty	2.78	0.49	0.73
197.parser	2.13	0.49	1.54
254.gap	3.45	0.52	2.08
255.vortex	1.67	0.45	1.32
256.bzip2	3.45	0.51	2.32
300.twolf	4.76	0.49	1.92
Total	2.94	0.36	1.16

Bonus: Liveness under SSI

- Proof that the interference graph is an interval graph
- The linearization of the CFG doesn't respect the dominance relation
- We can do liveness query in constant time
  - q included in the interval?

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- Proof that the interference graph is an interval graph
- The linearization of the CFG doesn't respect the dominance relation
- We can do liveness query in constant time
  - q included in the interval?
- Still not sure of the usefulness of SSI

Outline

Contributions

- Novel approach for liveness checking relying only on the CFG
- Uses information available from the loop nesting forest
- Fast construction algorithm
- Overall speedup in most cases

Future Work

- Dynamic update for CFG transformations
- Memory efficient reachability

The End

Thank you!

My topics of interest

- Graph algorithms
- CFG properties, dominance/post-dominance
- SSI and other SSA extensions