Pointer Analysis

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CS6843 Program Analysis
IIT Madras
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Outline

- Introduction
- Pointer analysis as a DFA problem
- Design decisions
- Andersen's analysis, Steensgaard's analysis
- Pointer analysis as a graph problem
  - Optimizations
- Pointer analysis as graph rewrite rules
- Applications
- Parallelization
  - Constraint based
  - Replication based

Points-to Analysis as a Graph Problem

Each pointer as a node, directed edge p → q indicates points-to set of q is a subset of that of p.

Input: set C of points-to constraints

Process address-of constraints

Add edges to constraint graph G using copy constraints

repeat

    Propagate points-to information in G

    Add edges to G using load and store constraints

until fixpoint

Points-to Analysis as a Graph Problem

*e = c, c = *a, e = d, b = a, *a = p

Initially, a→{a,q,r,s,t}, p→{b,c,d}

a {aqrst}

b { }

qrst { }

c { }

p {bcd}

d { }

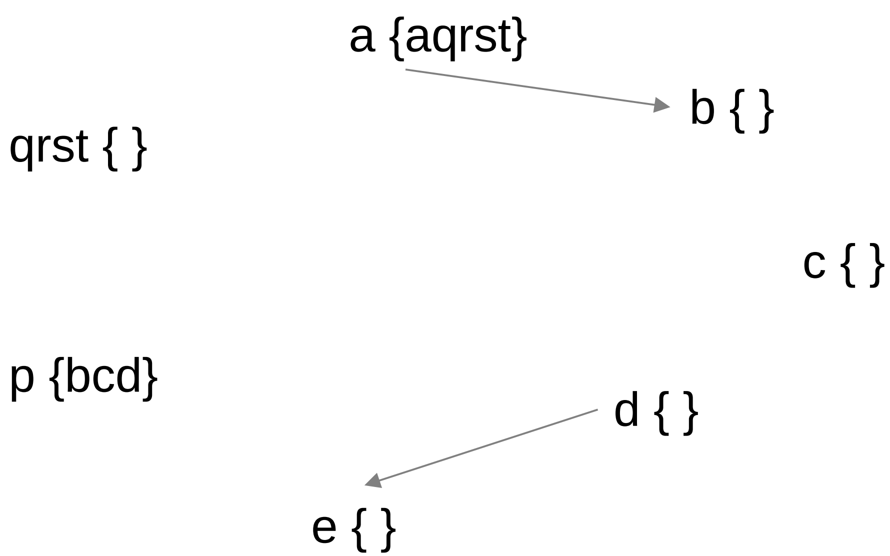
e { }

Points-to Analysis as a Graph Problem

*e = c, c = *a, e = d, b = a, *a = p

Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 0



e = d
b = a
----
*e = c
c = *a
*a = p

Points-to Analysis as a Graph Problem

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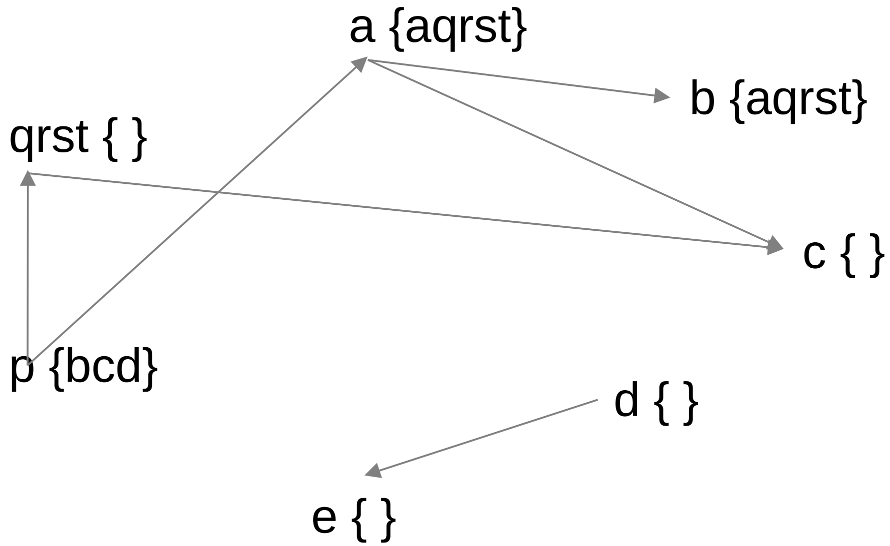
Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 1



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Points-to Analysis as a Graph Problem

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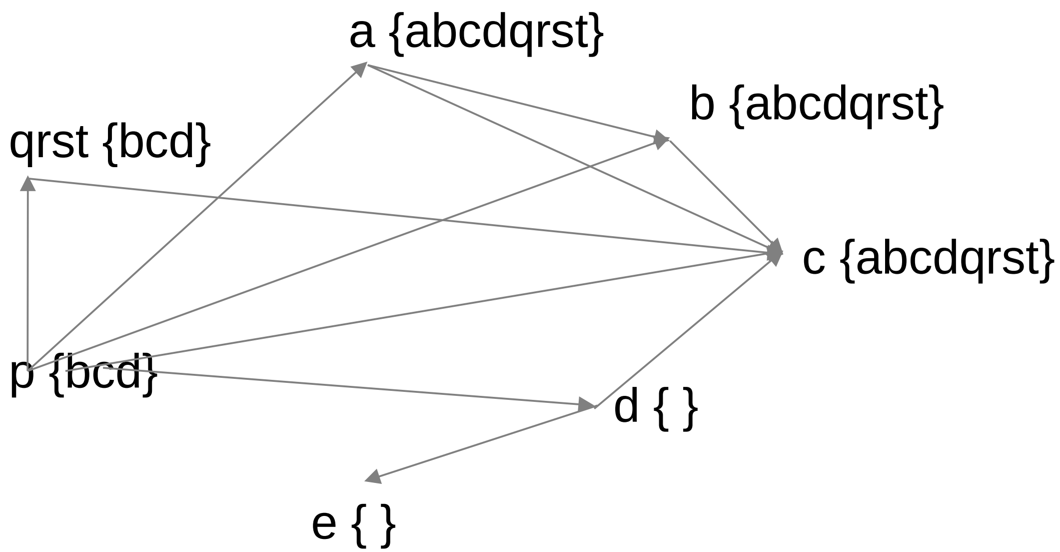
Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 2



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Points-to Analysis as a Graph Problem

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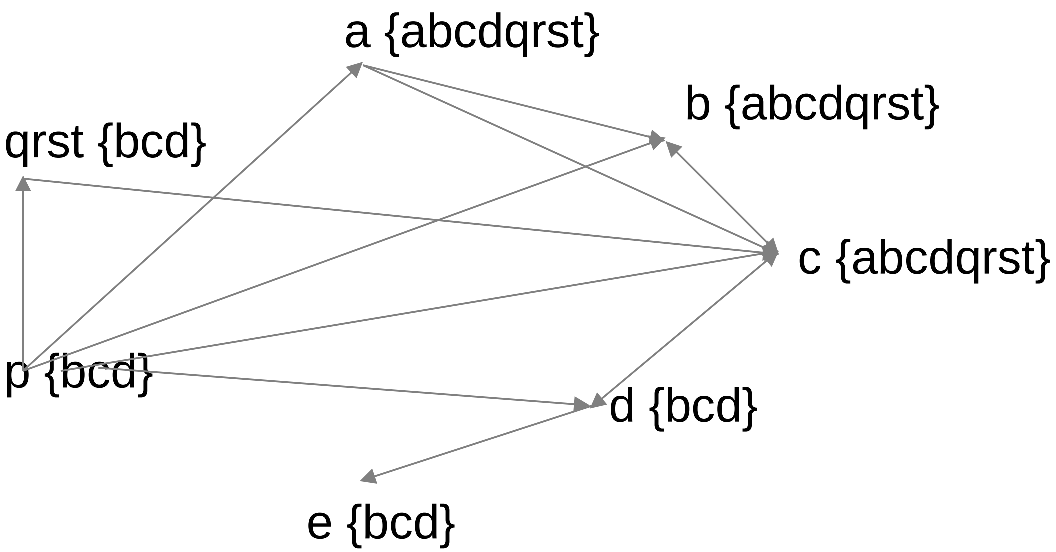
Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 3



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b = a
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*e = c
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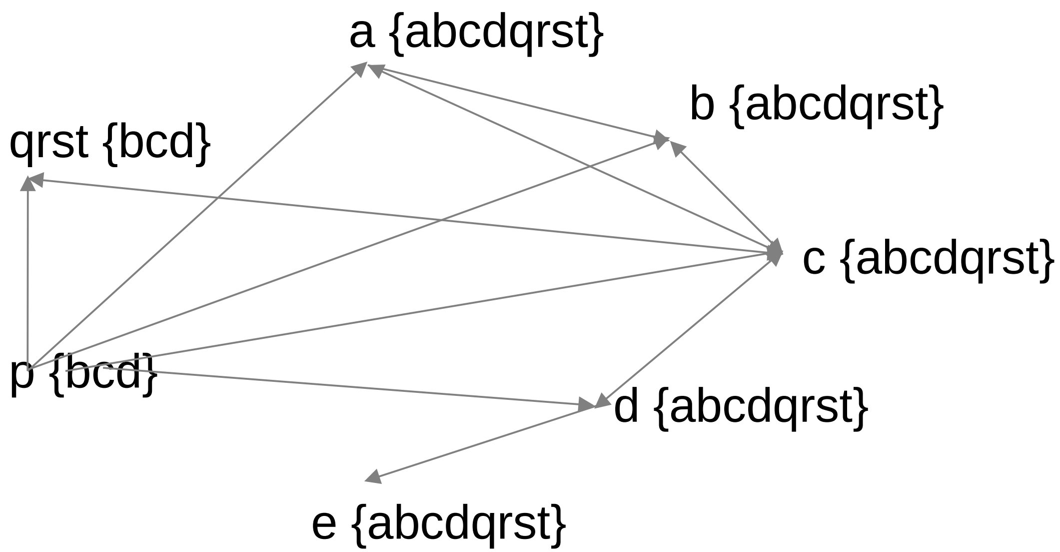
*a = p

Points-to Analysis as a Graph Problem

*e = c, c = *a, e = d, b = a, *a = p

Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 4



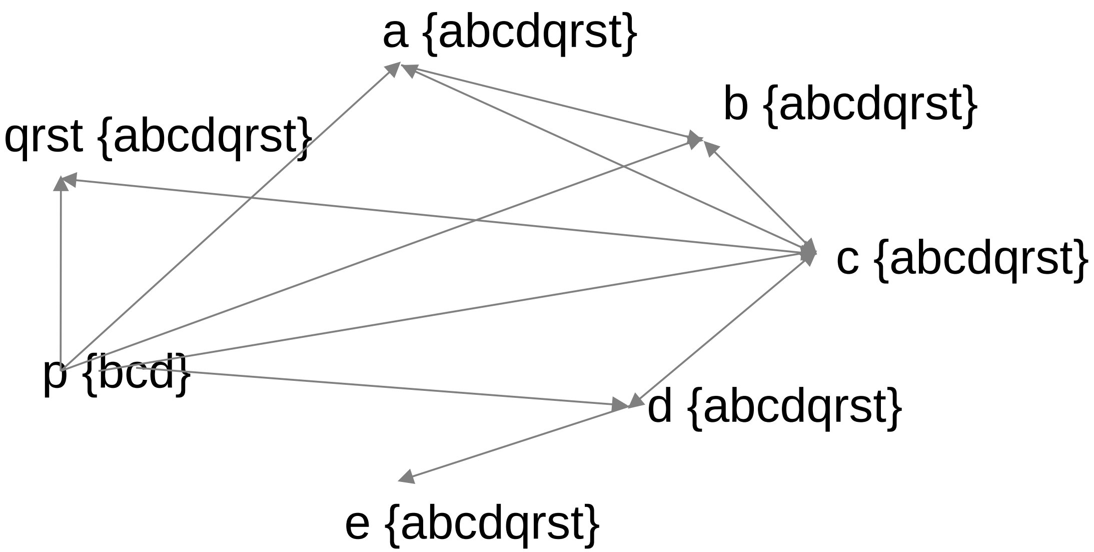
e = d
b = a
----
*e = c
c = *a
*a = p

Points-to Analysis as a Graph Problem

*e = c, c = *a, e = d, b = a, *a = p

Initially, a→{a,q,r,s,t}, p→{b,c,d}

Iteration 5: fixed-point



e = d
b = a
----
*e = c
c = *a
*a = p

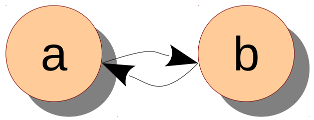
Why a Graph Formulation?

- A naïve formulation offers no benefits over the constraint-based formulation.
- We need to exploit structural properties of the constraint graph for efficient execution.
  - Online cycle detection
  - Online dominator detection
  - Propagation order: Topological sort, Depth first

Pointer Equivalence

- Two pointers are equivalent if they have the same points-to sets. Simple.
- If we identify such pointers *before* computing their points-to information, we can reduce the number of pointers tracked during the analysis.
- Now let's go back to the constraint graph.

Why a Graph Formulation?

- If the program contains statements $a = b$, $b = a$, what can you say about the points-to sets of a and b at the fixed-point?
- How does the constraint graph look like? 

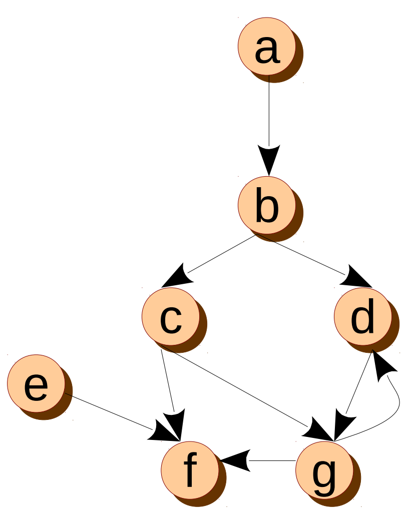
- How about $a = b$, $b = c$, $c = a$?
- How about $a = c$, $b = *p$, $c = b$?

Online Cycle Detection

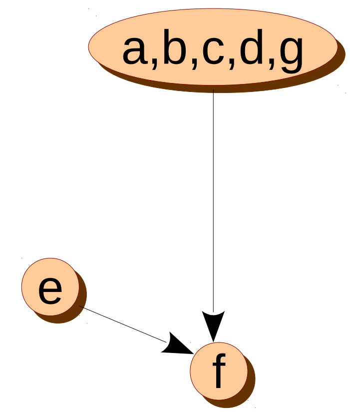
- Edges get added to the graph dynamically.
- So, cycle detection is performed online.
- Cycles are collapsed – usually replaced with a representative.
- Can use union-find.

Online Dominator Detection

- If two nodes in a constraint graph have the same dominator, they are pointer equivalent.
- A dominator and its dominees are pointer equivalent.
- doms is a transitive relation.



b doms g
!(b doms f)
a doms b
By transitivity, a doms g



Offline Variable Substitution

- But some constraints were easy to check for equivalence without running the analysis.
  - a = b, b = a
  - a = *p, *p = a
  - a = b, c = a, c = b and no other incoming edge to c.
- OVS is performed before running pointer analysis.

Propagation Order

- A topological ordering is beneficial for propagating points-to information (wave propagation)
- The information may also be propagated in depth-first manner (deep propagation)
- DP is helpful to reuse the difference in points-to information

How About Constraint Order?

- Given a set of constraints, find an optimal way of evaluating them
- Like most CS problems, this is NP-Complete
- Reducible from Set Cover

Reduction from Set Cover

- Given an instance of Set Cover $SC(U, S, K)$
  - U: universe of elements
  - S: set of subsets S_i
  - K: some number

  whether there exists a set of K subsets covering U

S = $\{1, 4\}, \{2, 5\}, \{2, 4, 5\}, \{3\}$
Solution Two: $\{1, 4\}, \{2, 4, 5\}, \{3\}$
Solution One: $\{1, 4\}, \{2, 5\}, \{3\}$

- Reduce to $PTA(C, S, K)$ where
  - C is a set of copy constraints
  - S is a variable of interest w.r.t. fixed-point
  - K is the number of steps in which the fixed-point is reached

$\mathrm{SC} \geqslant \mathrm{PTA}$

- $\mathrm{SC(U, S, K)} \geqslant \mathrm{PTA(C, S, K)}$
- Linear time reduction
  - for each $\mathrm{s} \in \mathrm{S}_\mathrm{i}$ add s to ptsto(S_i)
  - for each set S_i create a copy statement $\mathrm{S} = \mathrm{S}_\mathrm{i}$
- A solution to $\mathrm{PTA} \Rightarrow$ A solution to SC
- A solution to $\mathrm{PTA} \Leftarrow$ A solution to SC
- Poly-time verification

NP-Hard

NPC

NP

How About Constraint Order?

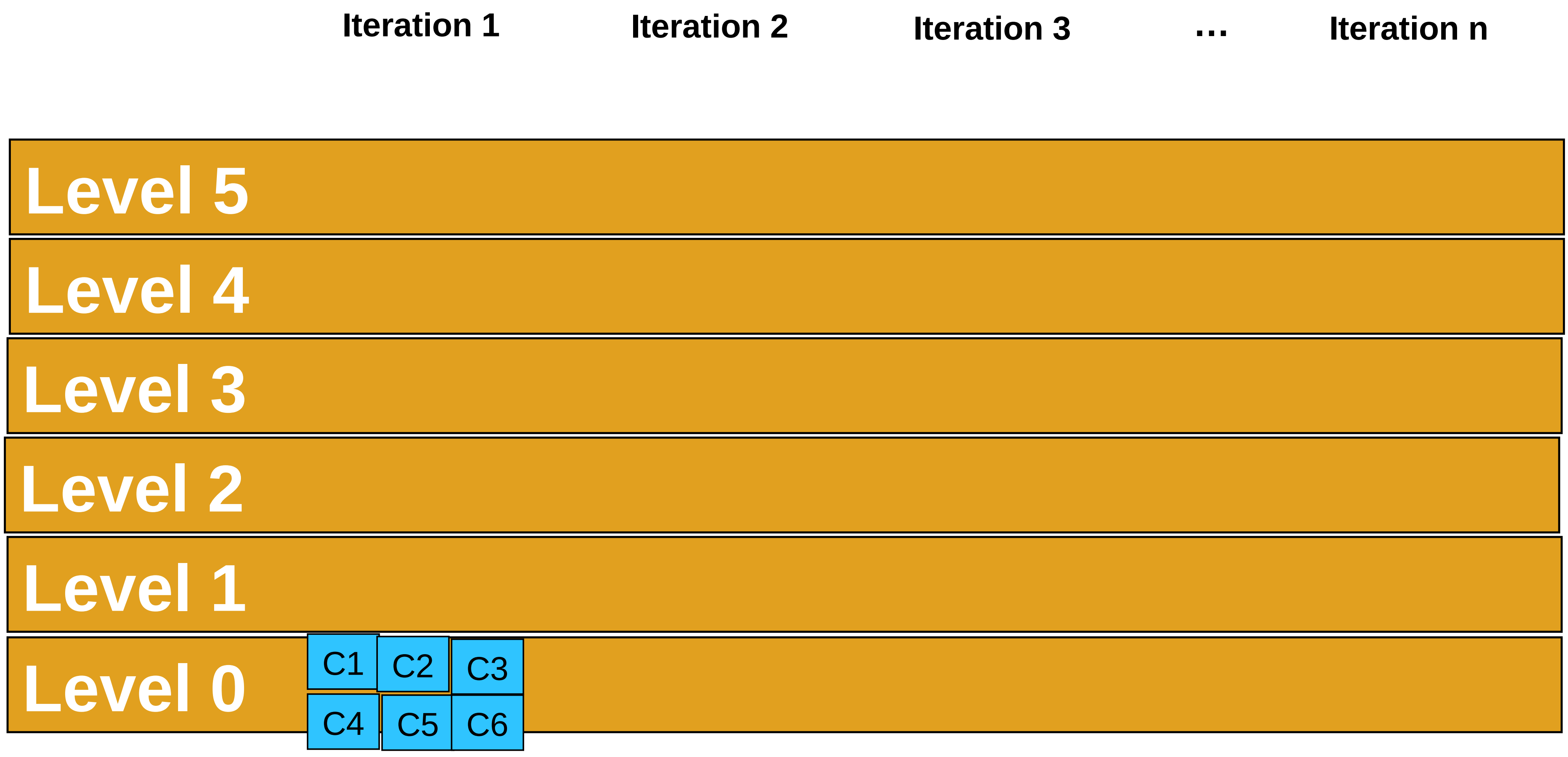
- Given a set of constraints, find an optimal way of evaluating them
- Like most CS problems, this is NP-Complete
- Reducible from Set Cover
- Need to depend upon heuristics

What would be a good heuristic?

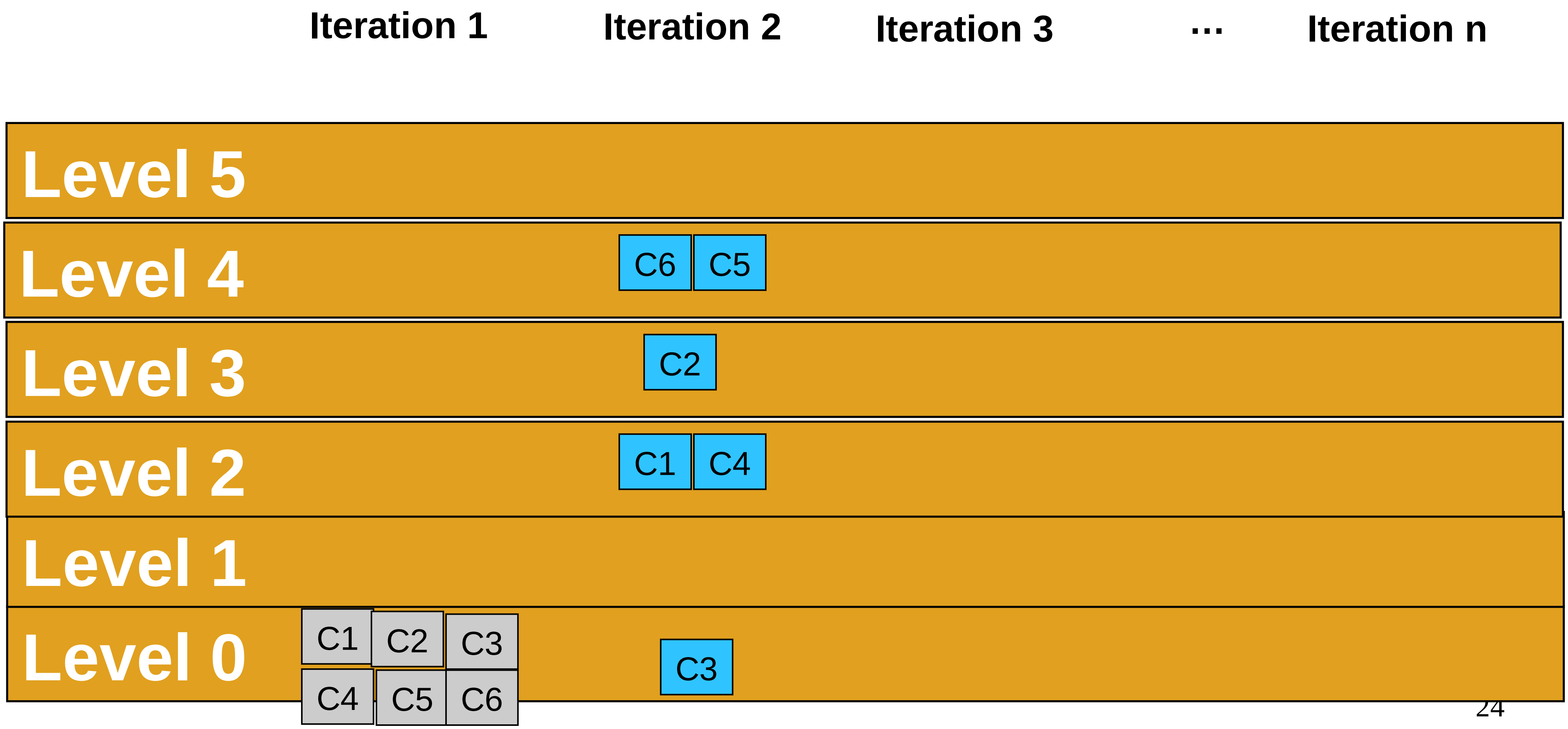
Constraint Priority

- Priority of a constraint in iteration *i* is the amount of new points-to information it adds in iteration *(i – 1)*.
- Constraints are grouped in different priority levels which are ordered based on their priority.
- A constraint may jump across multiple priority levels during the analysis.

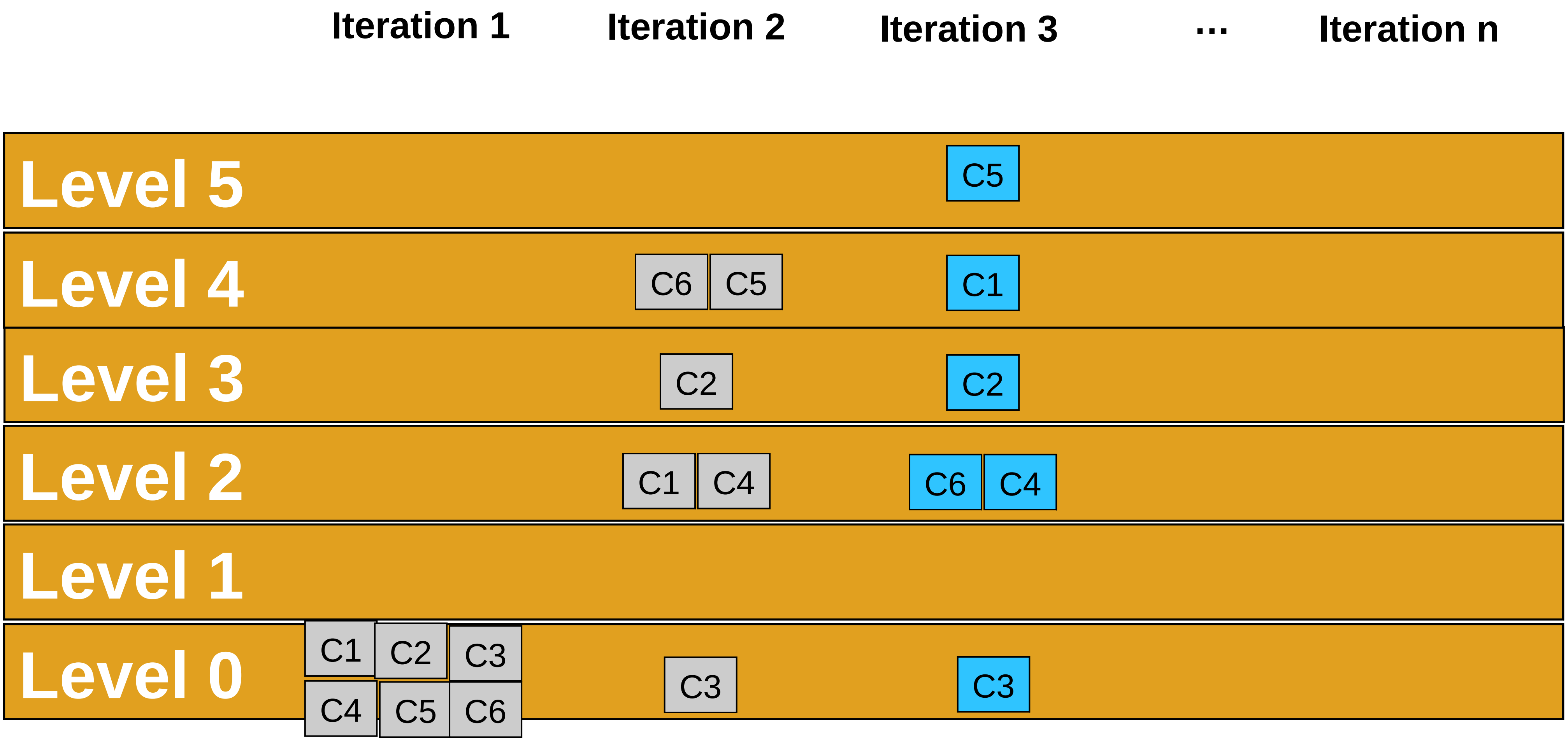
Bucketization



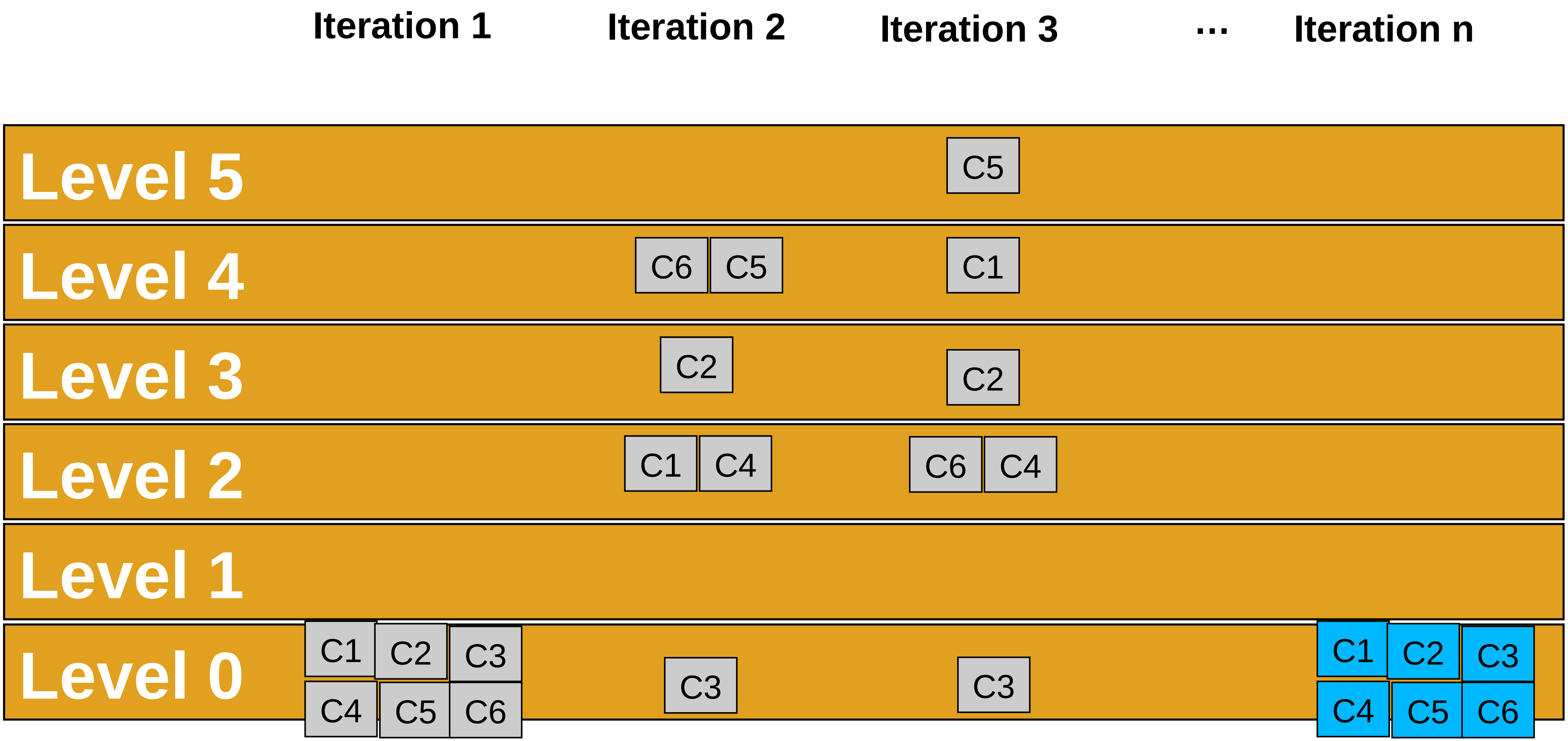
Bucketization



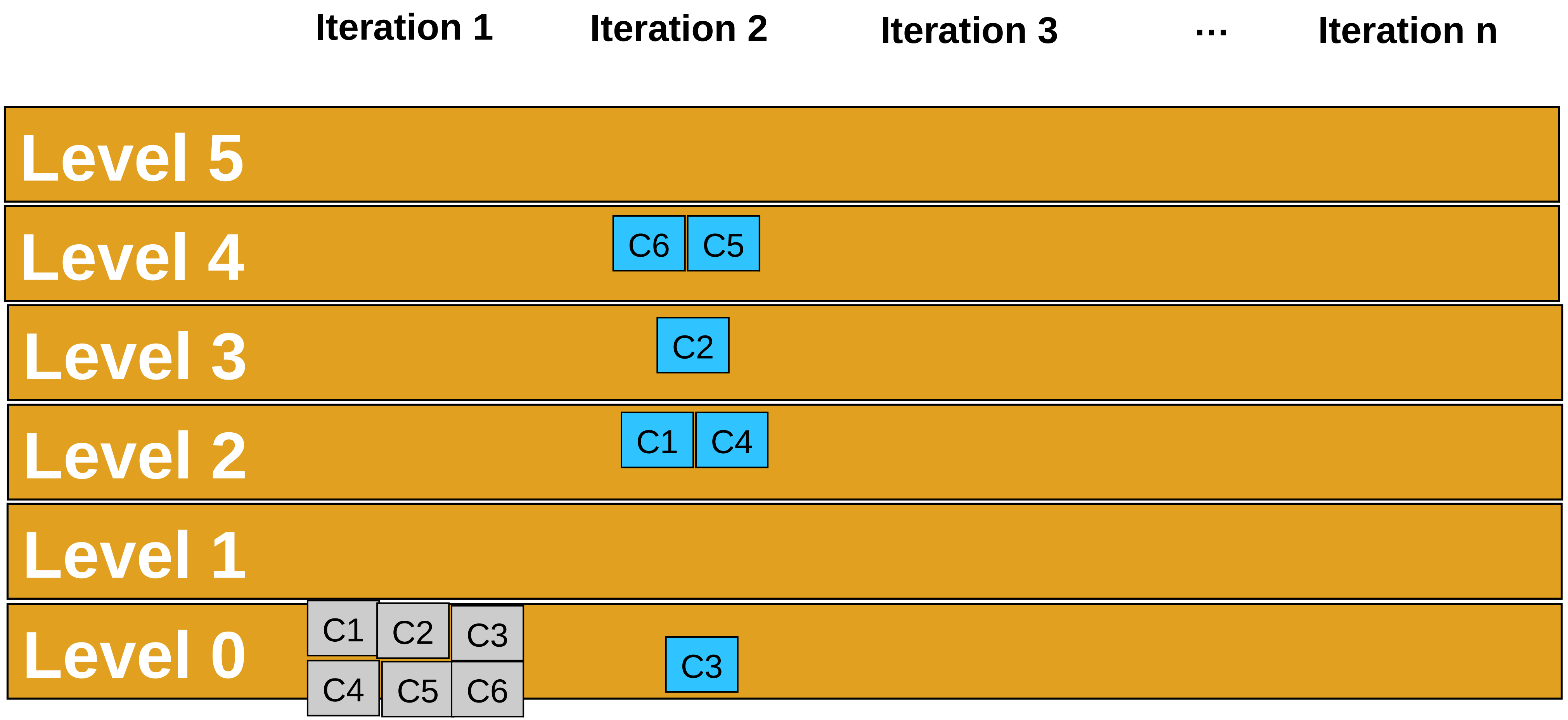
Bucketization



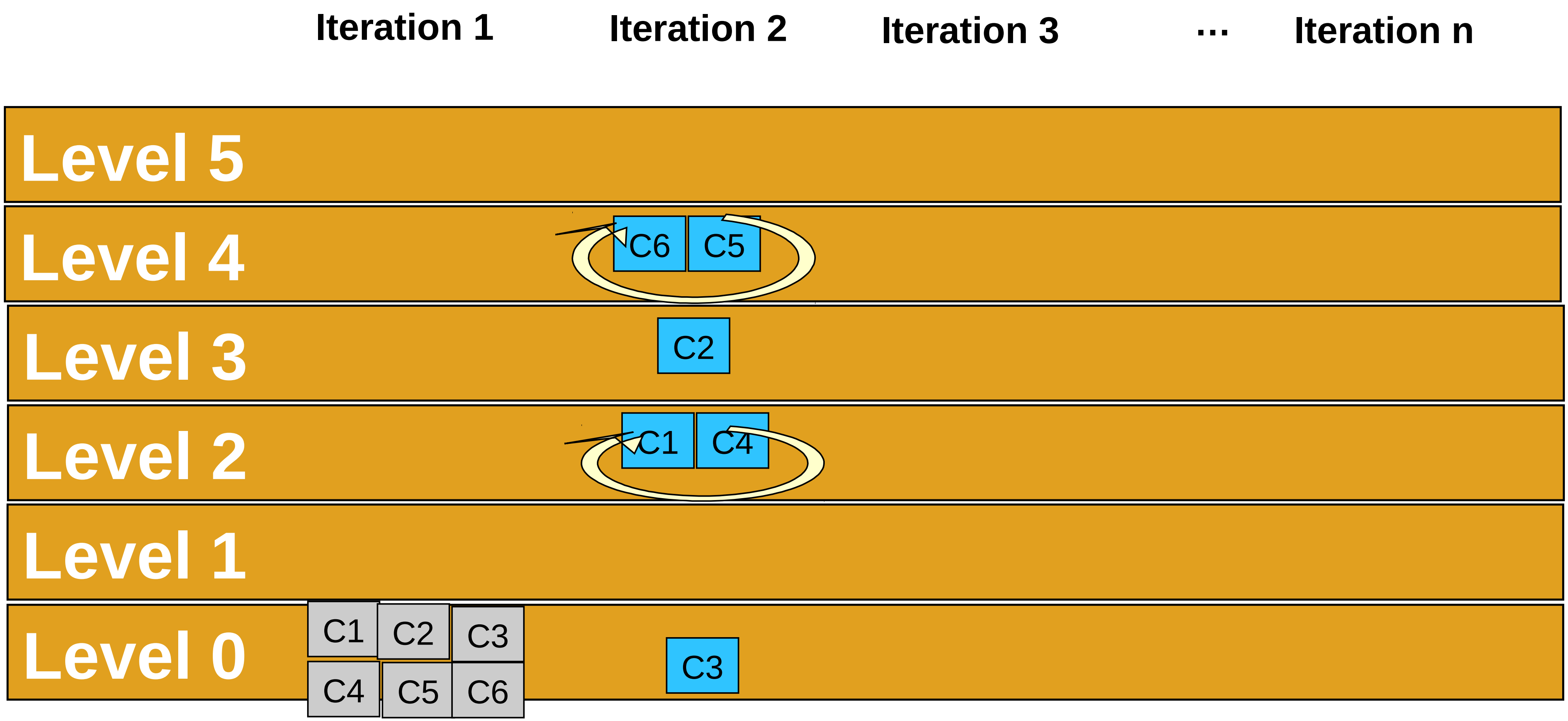
Bucketization



Skewed Evaluation



Skewed Evaluation



Prioritized Points-to Analysis

Processing order

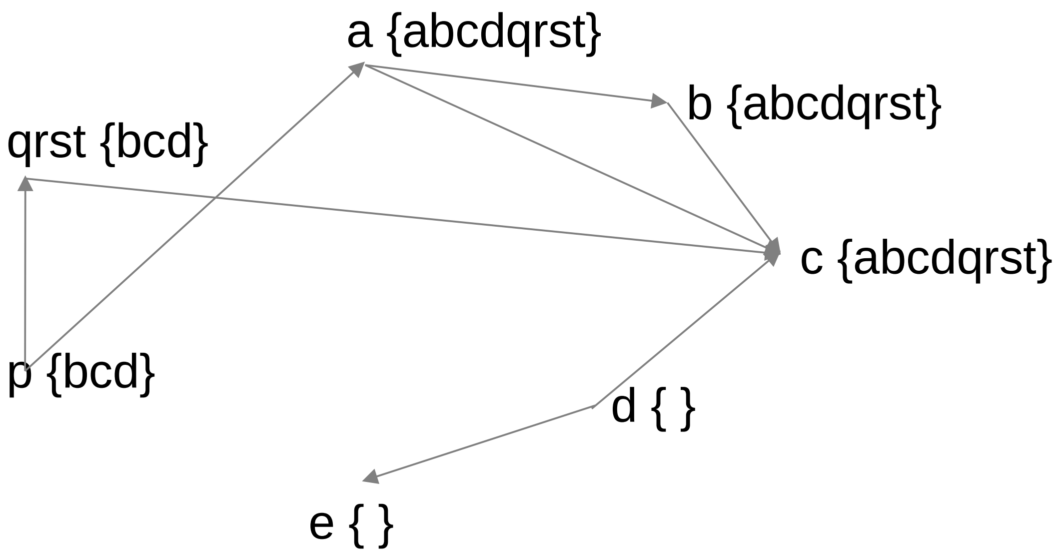
*a = p (18)
c = *a (8)
*e = c (0)

Prioritized Points-to Analysis

Processing order

*a = p (18)
c = *a (8)
*e = c (0)

Priority: Iteration 1

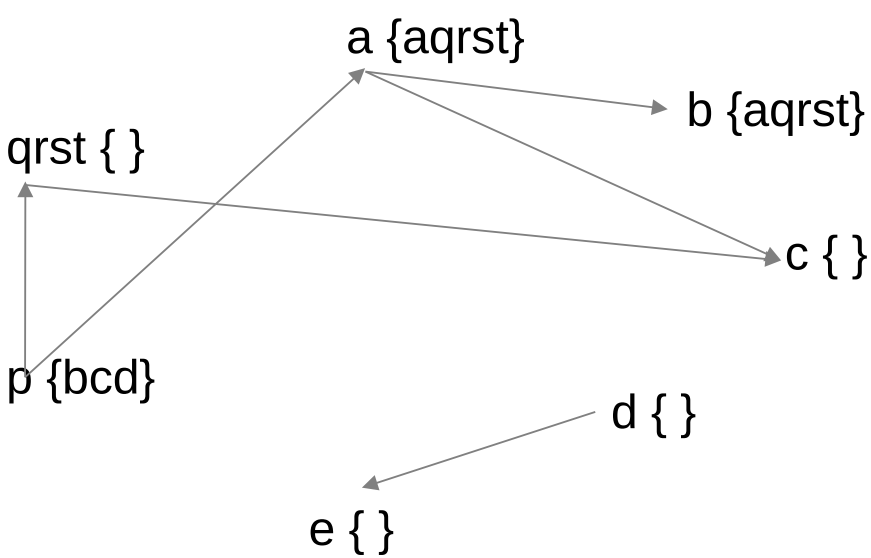


Prioritized Points-to Analysis

Fixed Processing order

*e = c
c = *a
*a = p

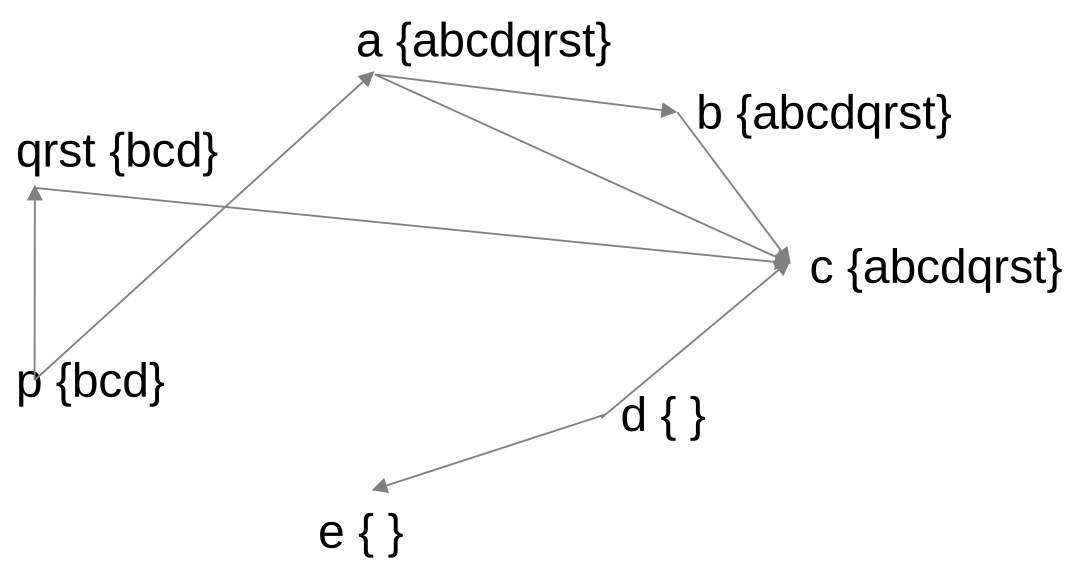
Andersen: Iteration 1



Processing order

*a = p (18)
c = *a (8)
*e = c (0)

Priority: Iteration 1



Prioritized Points-to Analysis

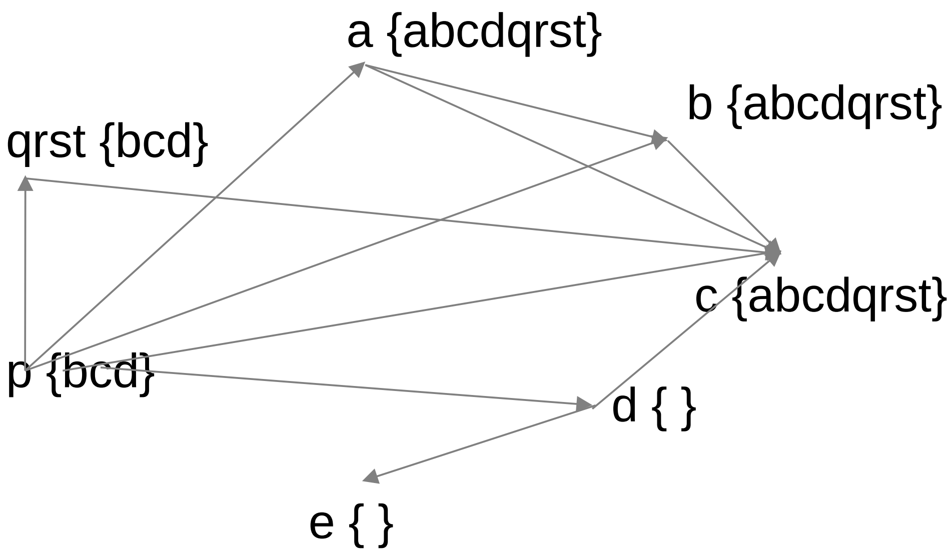
Fixed Processing order

*e = c
c = *a
*a = p

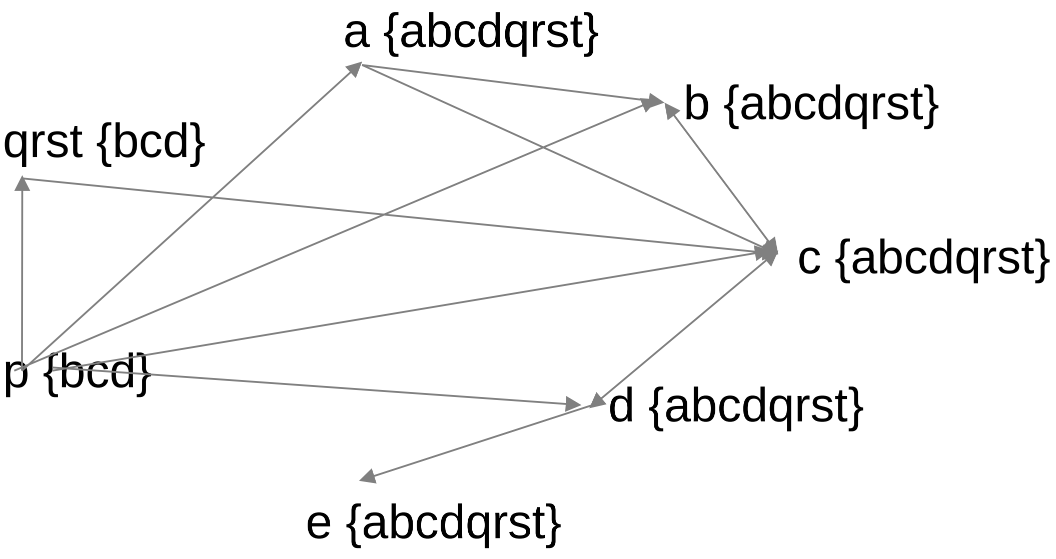
Processing order

*a = p (6)
c = *a (0)
*e = c (10)

Andersen: Iteration 2



Priority: Iteration 2

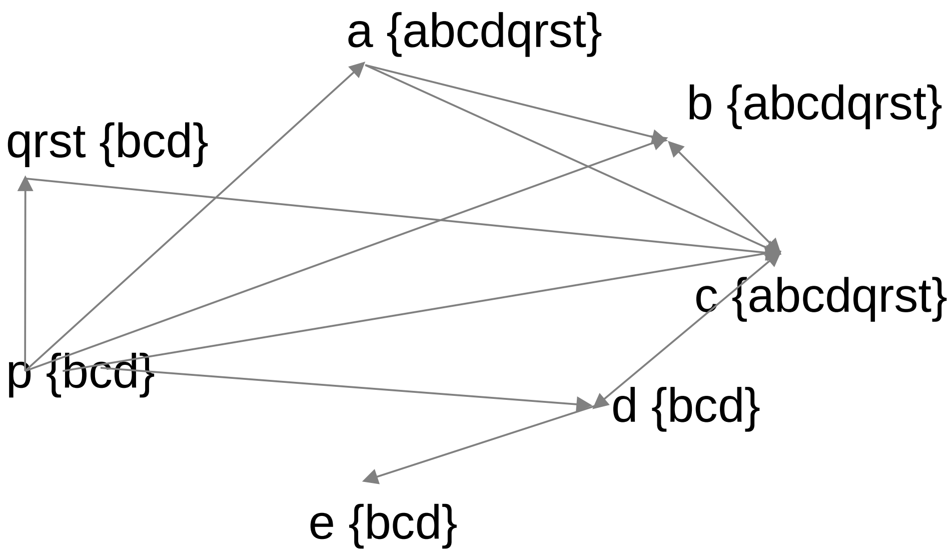


Prioritized Points-to Analysis

Fixed Processing order

*e = c
c = *a
*a = p

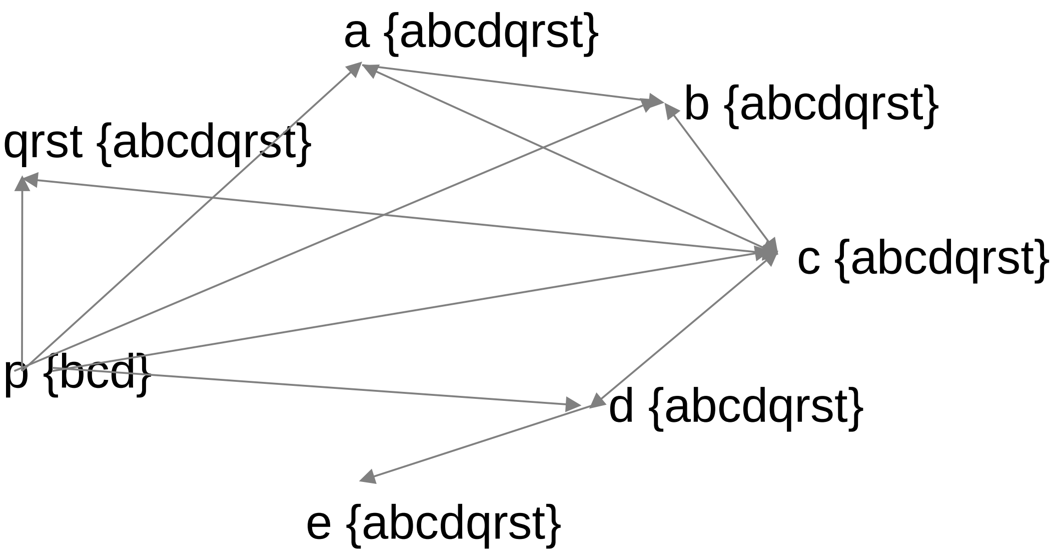
Andersen: Iteration 3



Processing order

*e = c (20)
*a = p (0)
c = *a (0)

Priority: Iteration 3

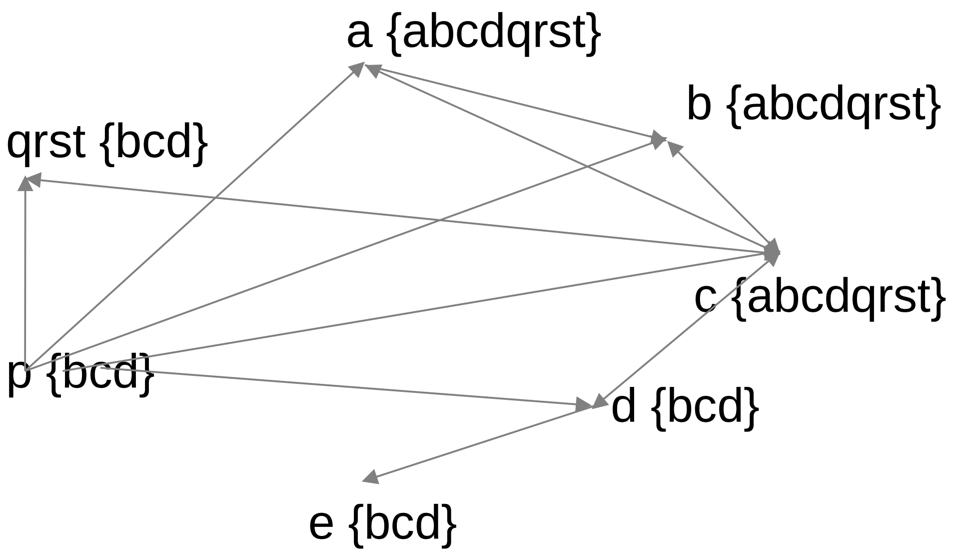


Prioritized Points-to Analysis

Fixed Processing order

*e = c
c = *a
*a = p

Andersen: Iteration 4



Processing order

*e = c (0)
*a = p (0)
c = *a (0)

Priority: fixed-point