CSE P 501 – Compilers

SSA

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Agenda

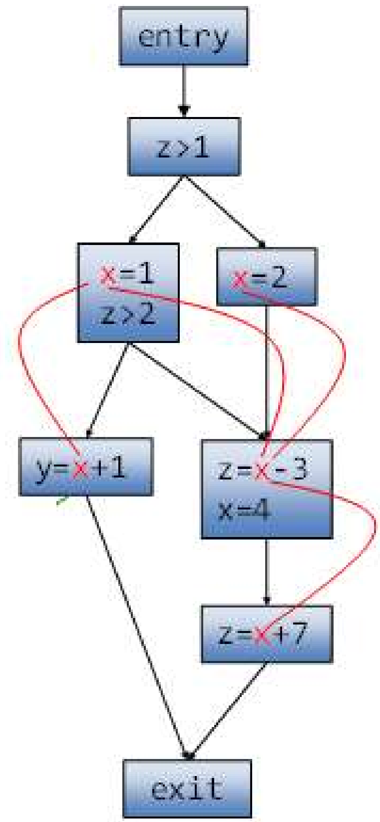
- Overview of SSA IR
  - Constructing SSA graphs
  - Sample of SSA-based optimizations
  - Converting back from SSA form

- Sources: Appel ch. 19, also an extended discussion in Cooper-Torczon sec. 9.3, Mike Ringenburg's CSE 401 slides (13wi)

Def-Use (DU) Chains

- Common dataflow analysis problem: Find all sites where a variable is used, or find the definition site of a variable used in an expression
- Traditional solution: def-use chains – additional data structure on top of the dataflow graph
  - Link each statement defining a variable to all statements that use it
  - Link each use of a variable to its definition

Def-Use (DU) Chains



In this example, two DU chains intersect

DU-Chain Drawbacks

for (i= –)
for (i= –)

- Expensive: if a typical variable has N uses and M definitions, the total cost *per-variable* is O(N * M), i.e., $O(n^2)$
  - Would be nice if cost were proportional to the size of the program
- Unrelated uses of the same variable are mixed together
  - Complicates analysis – variable looks live across all uses even if unrelated

SSA: Static Single Assignment

$a_7 := —$

- IR where each variable has only one definition in the program text
  - This is a single *static* definition, but that definition can be in a loop that is executed dynamically many times
- Makes many analyses (and associated optimizations) more efficient
- Separates values from memory storage locations
- Complementary to CFG/DFG – better for some things, but cannot do everything

SSA in Basic Blocks

Idea: for each original variable x, create a new variable x_n at the n^{th} definition of the original x. Subsequent uses of x use x_n until the next definition point.

- Original
  - $a := x + y$
  - $b := a - 1$
  - $a := y + b$
  - $b := x * 4$
  - $a := a + b$
- SSA
  - $a_1 := x + y$
  - $b_1 := a_1 - 1$
  - $a_2 := y + b_1$
  - $b_2 := x * 4$
  - $a_3 := a_2 + b_2$

Merge Points

- The issue is how to handle merge points

if (...)
  a = x;
else
  a = y;
b = a;

→

if (...)
  a_1 = x;
else
  a_2 = y;
b_1 = ??;

Merge Points

- The issue is how to handle merge points

```
if (...)
  a = x;
else
  a = y;
b = a;
```

```
if (...)
  a1 = x;
else
  a2 = y;
a3 =Φ(a1, a2);
b1 = a3;
```

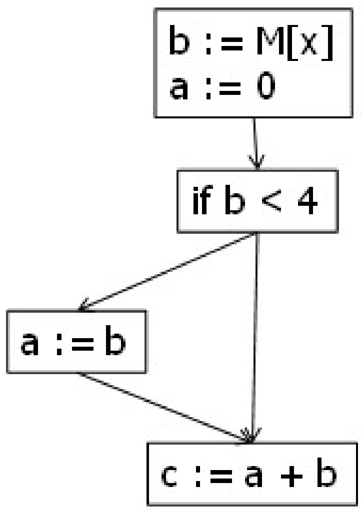
- Solution: introduce a Φ-function

  $a_3 := \Phi(a_1, a_2)$

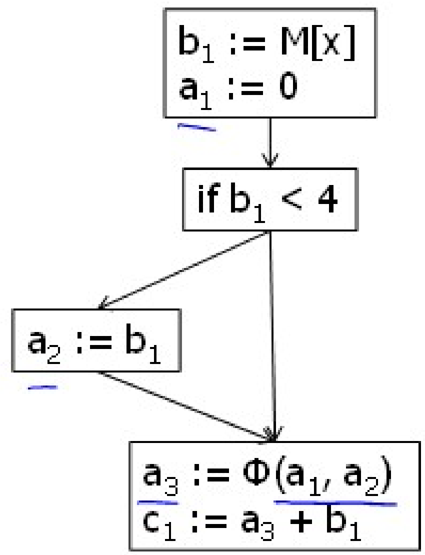
- Meaning: a_3 is assigned either a_1 or a_2 depending on which control path is used to reach the Φ-function

Another Example

Original



SSA

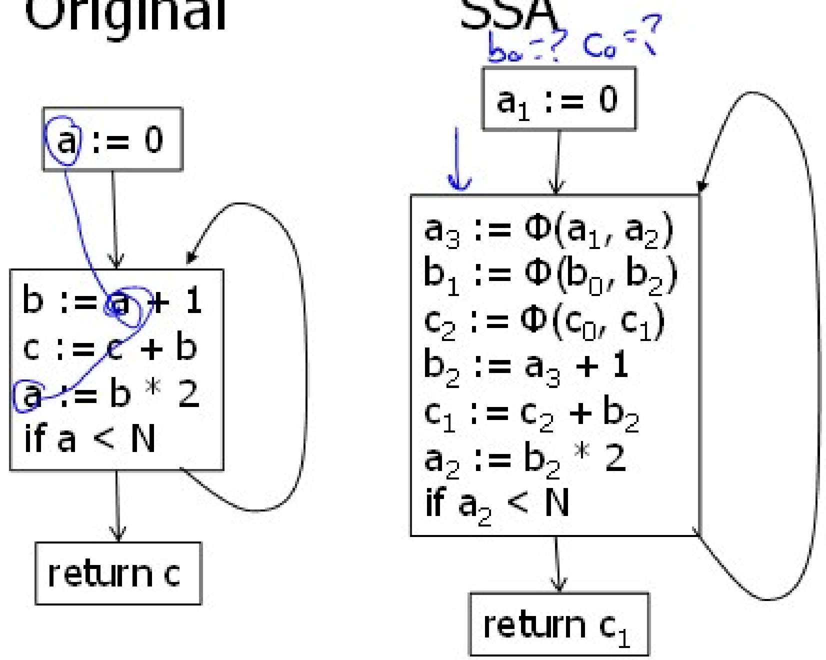


How Does Φ "Know" What to Pick?

- It doesn't
- Φ-functions don't actually exist at runtime
  - When we're done using the SSA IR, we translate back out of SSA form, removing all Φ-functions
    - Basically by adding code to copy all SSA x_i values to the single, non-SSA, actual x
  - For analysis, all we typically need to know is the connection of uses to definitions – no need to "execute" anything

Example With a Loop

Original | SSA



Notes:

- Loop back edges are also merge points, so require Φ-functions
- a_0, b_0, c_0 are initial values of a, b, c on block entry
- b_1 is dead – can delete later
- c is live on entry – either input parameter or uninitialized

What does SSA “buy” us?

- No need for DU or UD chains – implicit in SSA
- Compact representation
- SSA is “recent” (i.e., 80s)
- Prevalent in real compilers for { } languages

Converting To SSA Form

- Basic idea
  - First, add Φ-functions
  - Then, rename all definitions and uses of variables by adding subscripts

Inserting Φ-Functions

- Could simply add Φ-functions for every variable at every join point(!)
- Called "maximal SSA"
- But
  - Wastes *way* too much space and time
  - Not needed in many cases

Path-convergence criterion

x: $a = -$ y: $a = \sim$

z: $a_k = \Phi(a_i, a_j, \ldots)$

- Insert a Φ-function for variable a at point z when:
  - There are blocks x and y, both containing definitions of a, and x ≠ y
  - There are nonempty paths from x to z and from y to z
  - These paths have no common nodes other than z

Details

$a_0 = ?$
$b_0 = ?$

$a_7 = \phi(a_6, a_3, a_{12})$

$\phi(a_7, -)$

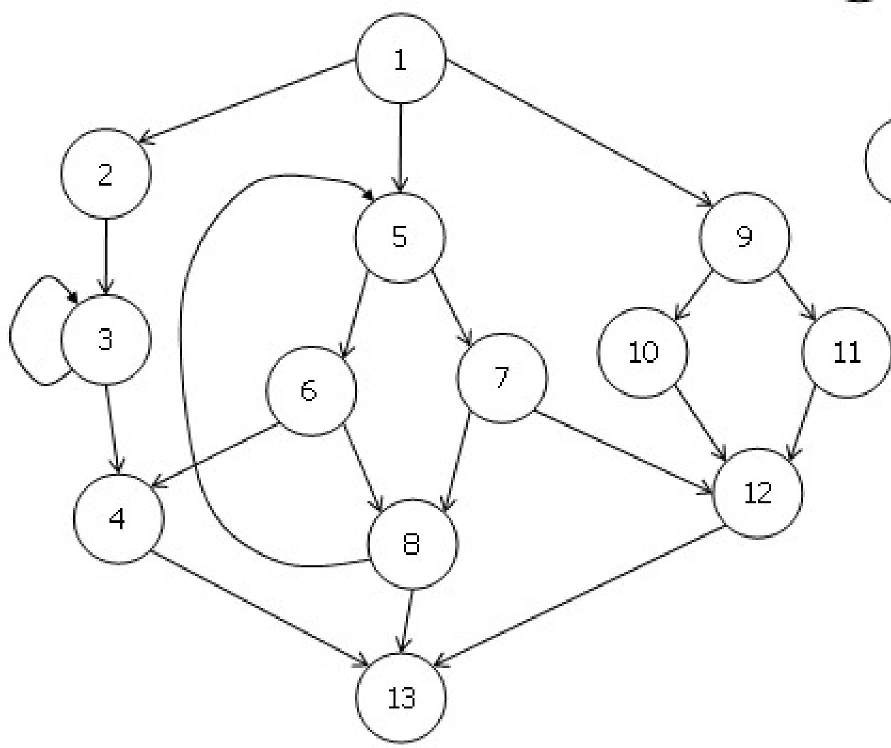
- The start node of the flow graph is considered to define every variable (even if "undefined")
- Each Φ-function itself defines a variable, which may create the need for a new Φ-function
  - So we need to keep adding Φ-functions until things converge
- How can we do this efficiently?
  Use a new concept: dominance frontiers

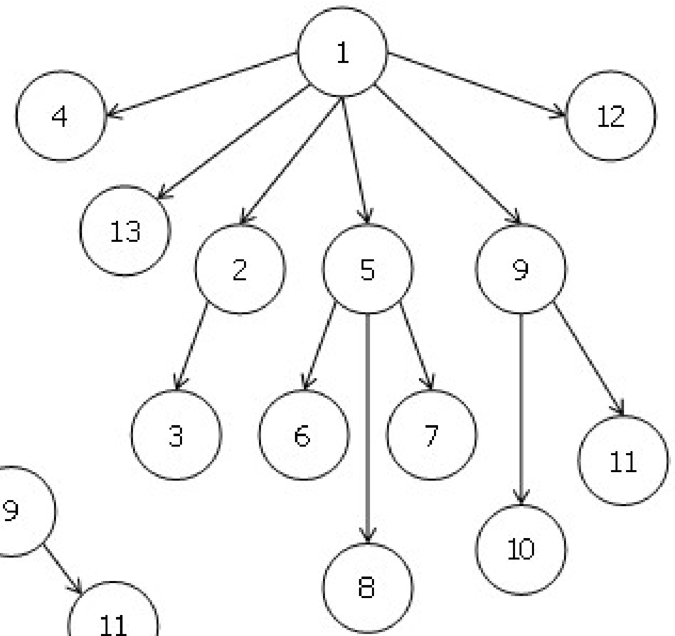
Dominators (review)

- Definition: a block x *dominates* a block y iff every path from the entry of the control-flow graph to y includes x
- So, by definition, x dominates x
- We can associate a Dom(inator) set with each CFG node x – set of all blocks dominated by x

  $|\ \mathrm{Dom}(x)\ | \geq 1$
- Properties:
  - Transitive: if a dom b and b dom c, then a dom c
  - There are no cycles, thus can represent the dominator relationship as a tree

Example





Dominators and SSA

$x_i :=$

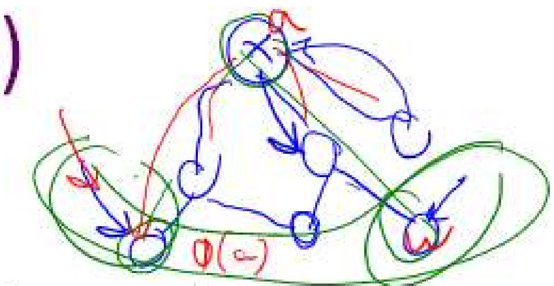
$B \quad x := \Phi(\ldots x_i \ldots)$

- One property of SSA is that definitions dominate uses; more specifically:
  - If $x := \Phi(\ldots,x_i,\ldots)$ is in block B, then the definition of x_i dominates the i^{th} predecessor of B
  - If x is used in a non-Φ statement in block B, then the definition of x dominates block B

Dominance Frontier (1)

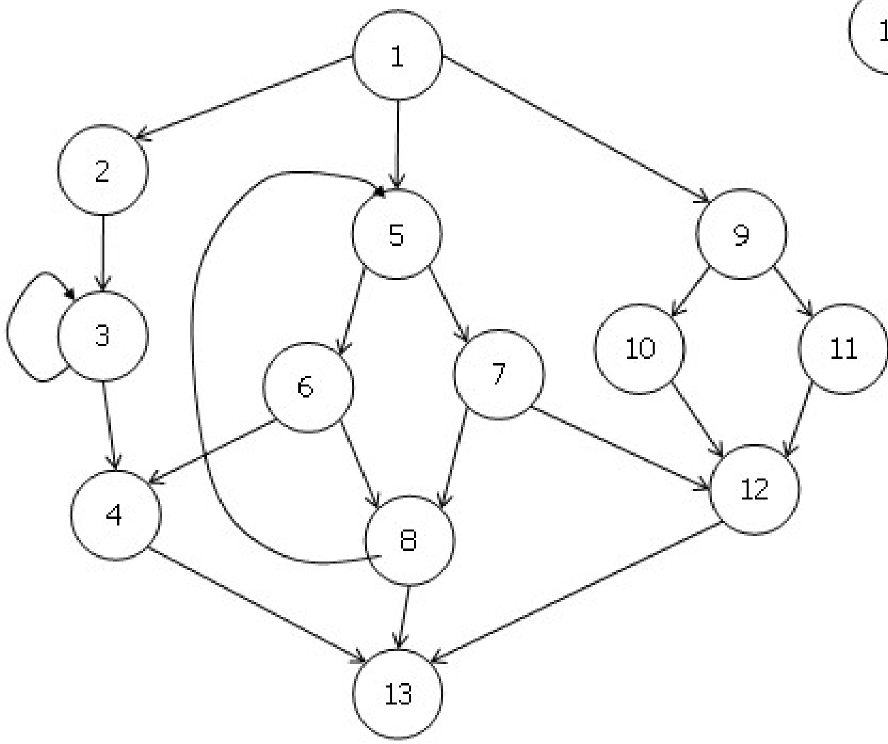
- To get a practical algorithm for placing Φ-functions, we need to avoid looking at all combinations of nodes leading from x to y
- Instead, use the dominator tree in the flow graph

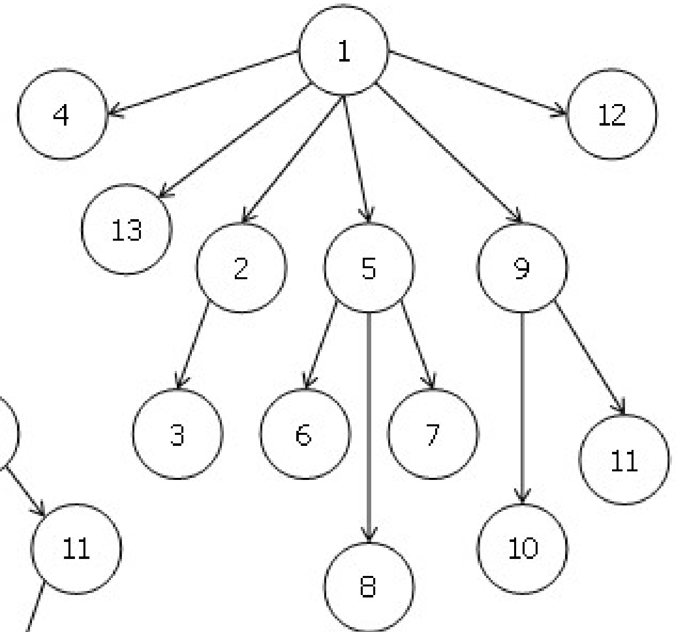
Dominance Frontier (2)



- Definitions
  - x *strictly dominates* y if x dominates y and $x \neq y$
  - The *dominance frontier* of a node x is the set of all nodes w such that x dominates a predecessor of w, but x does not strictly dominate w
    - This means that x can be in *it's own* dominance frontier! That can happen if there is a back edge to x (i.e., x is the head of a loop)
- Essentially, the dominance frontier is the border between dominated and undominated nodes

Example



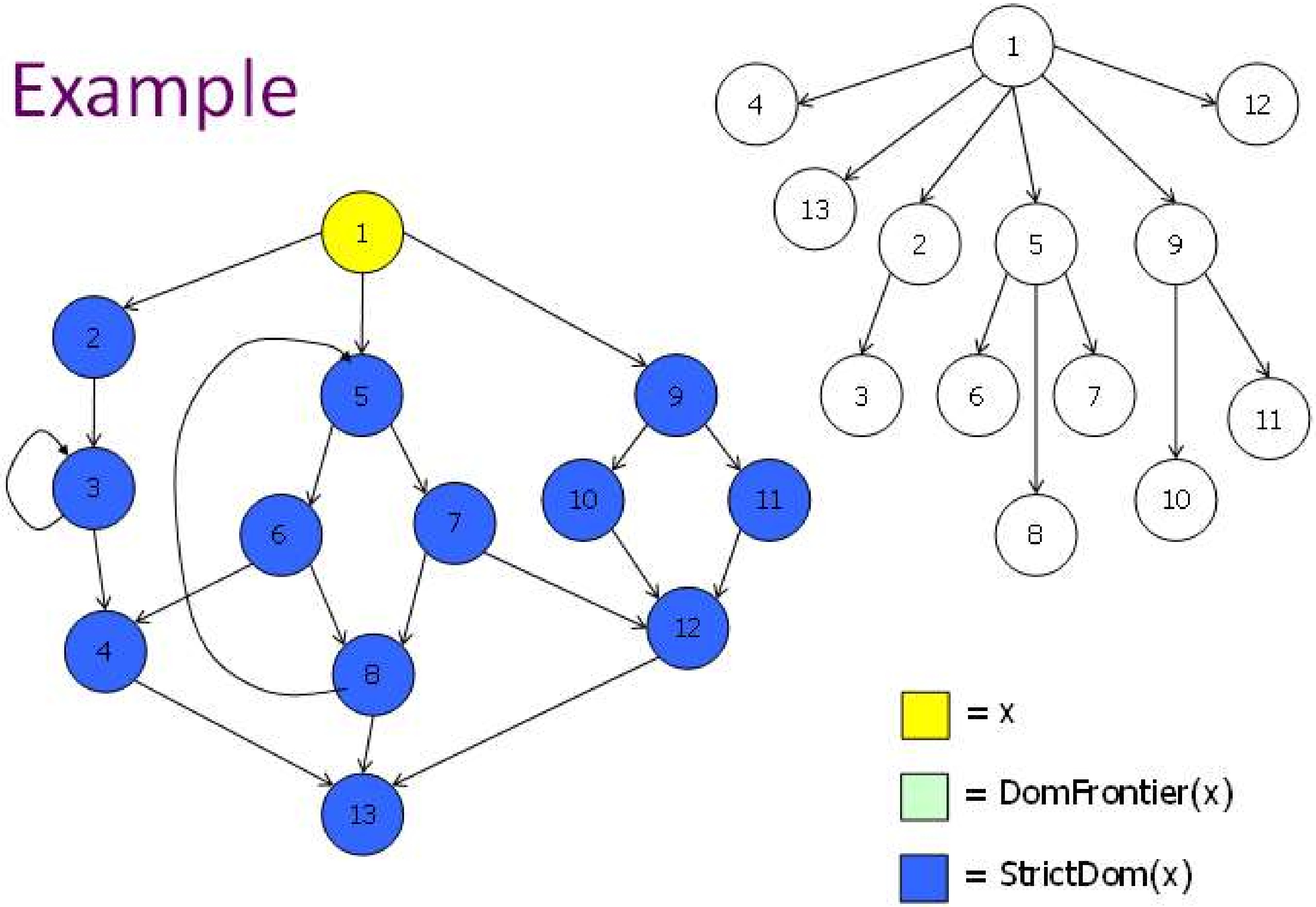


= X

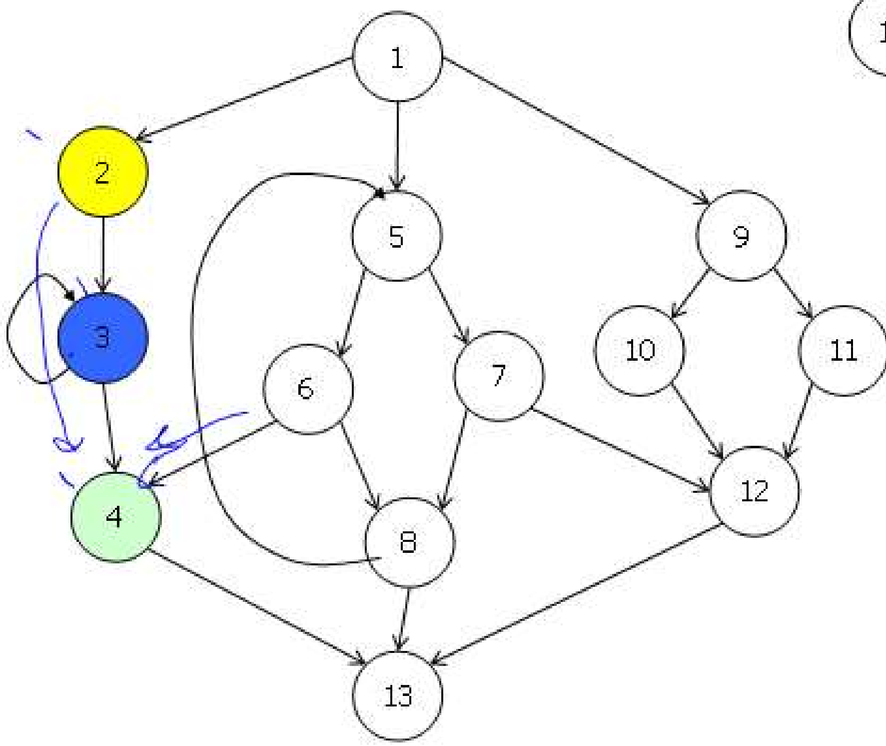
= DomFrontier(x)

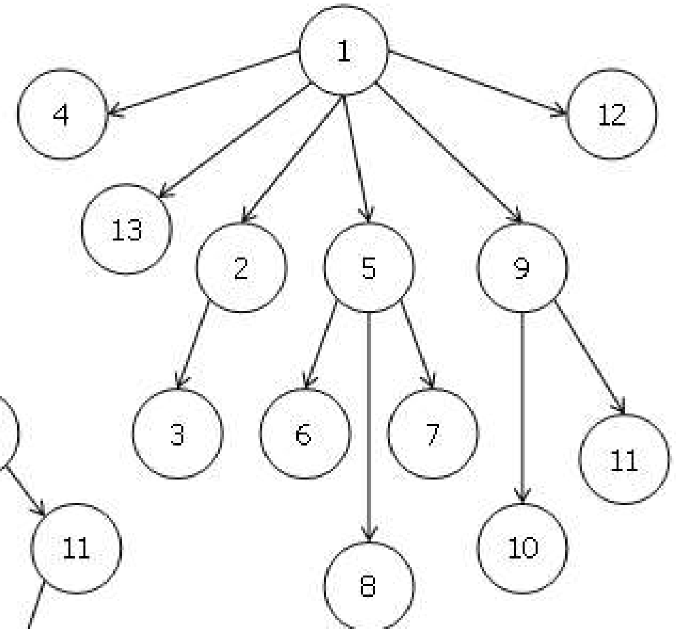
= StrictDom(x)

Example



Example





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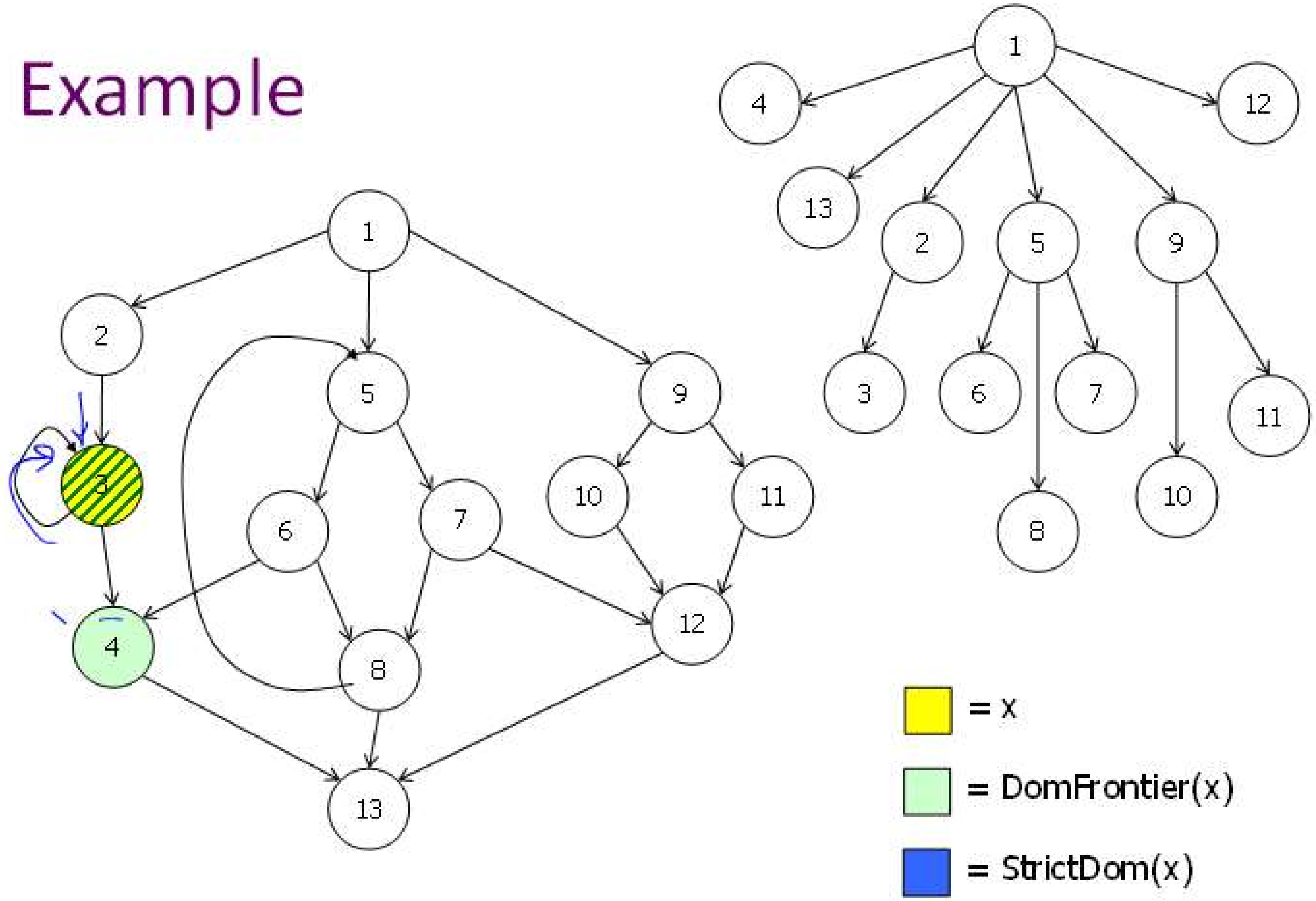

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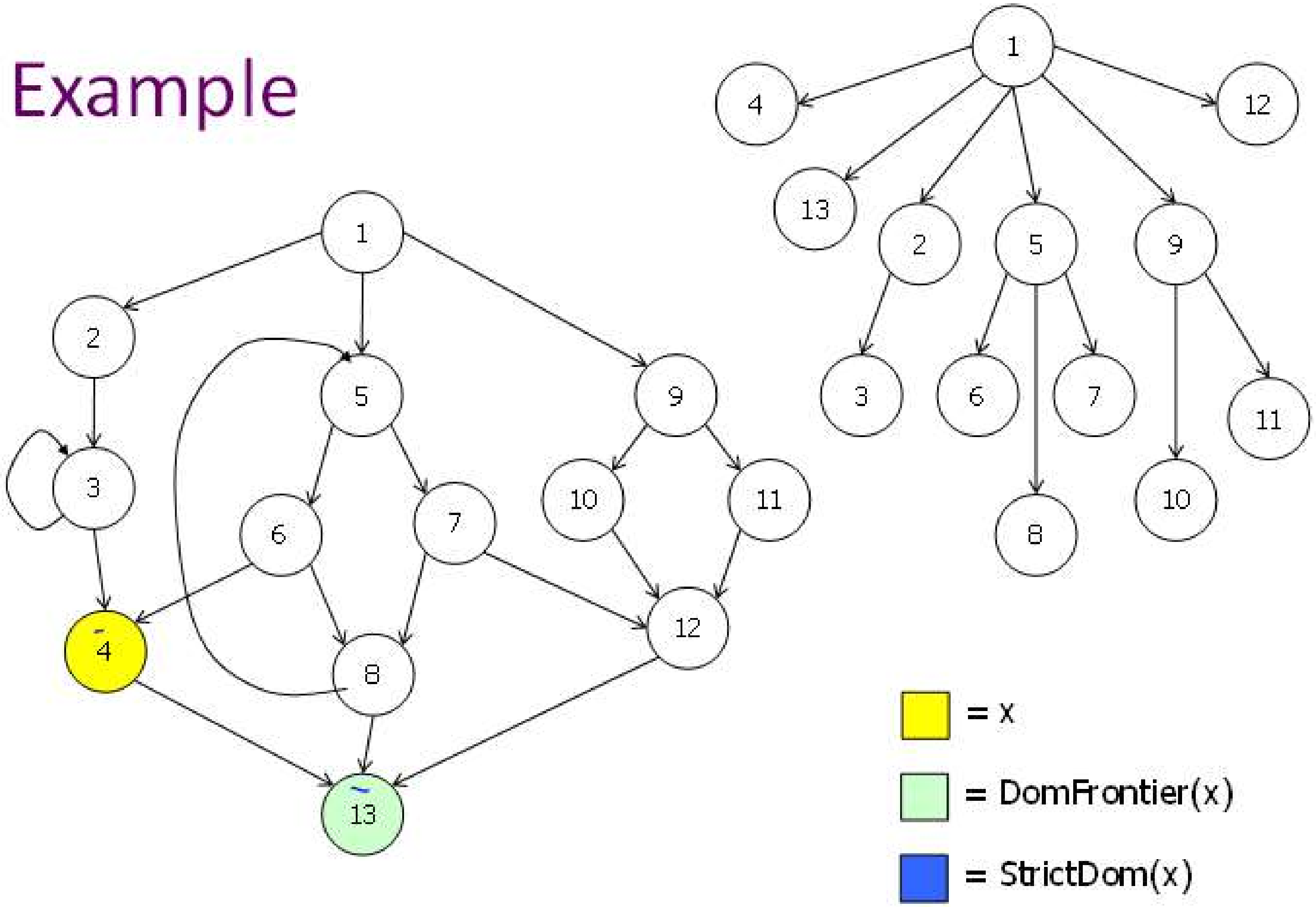

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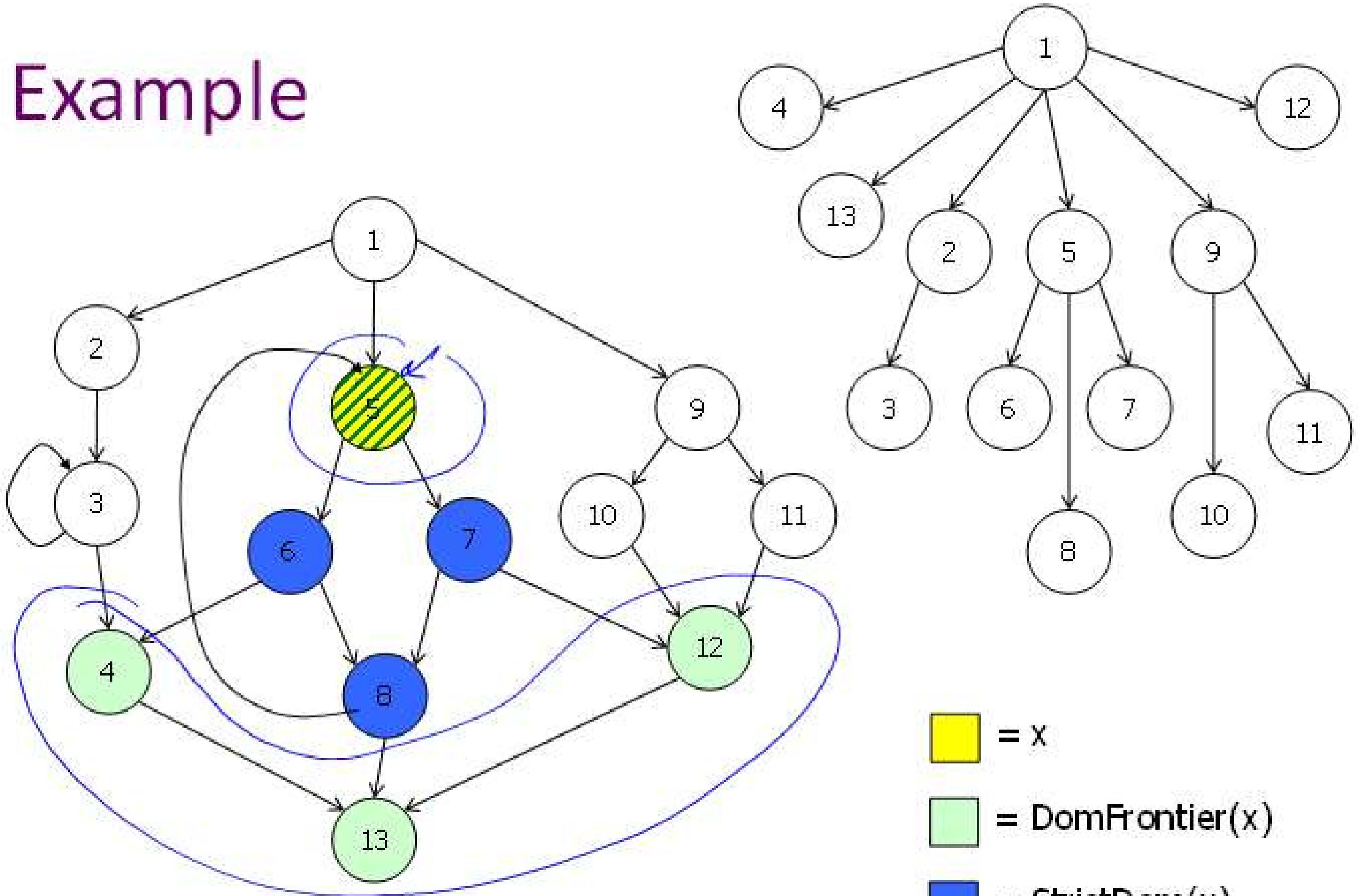

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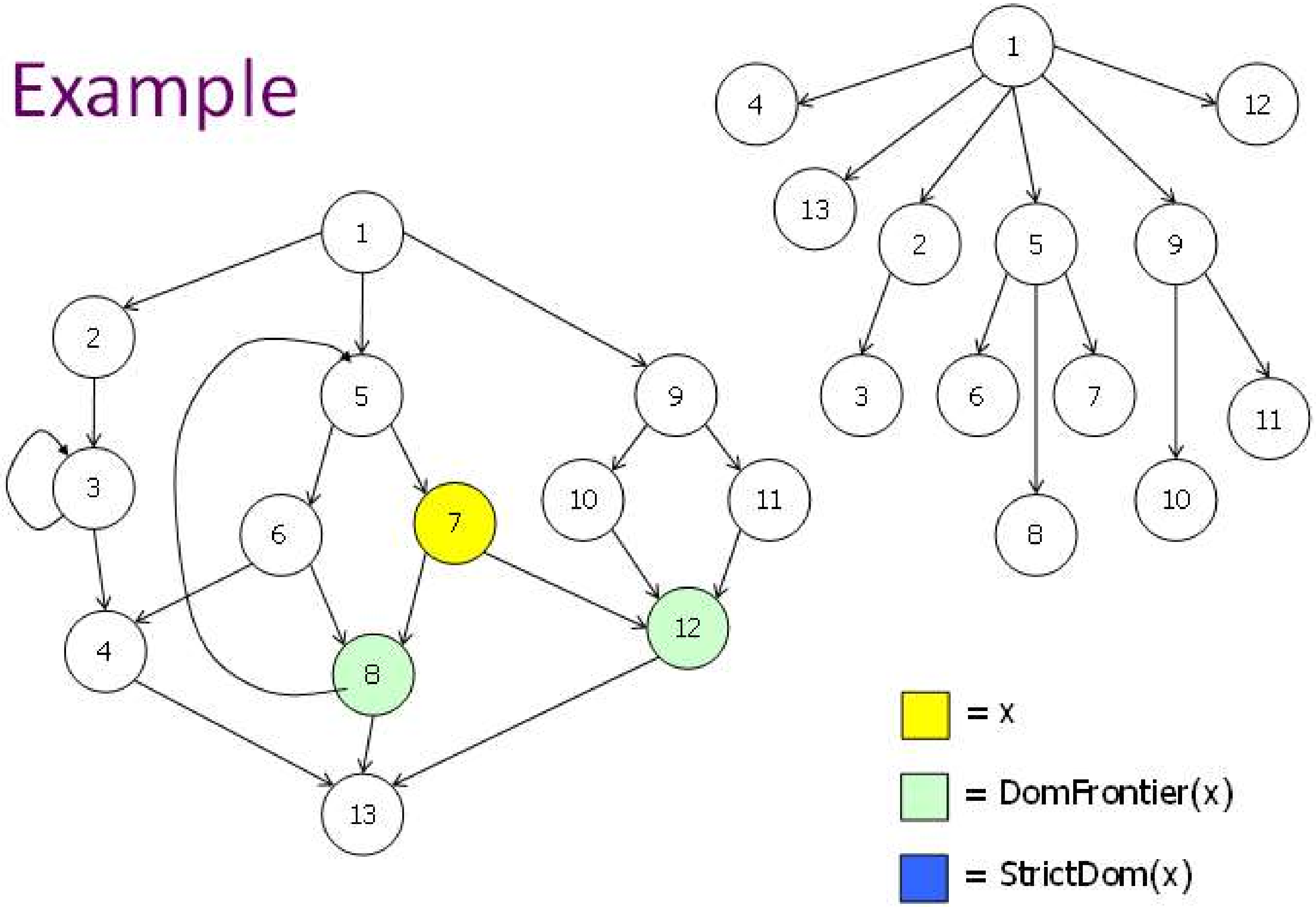

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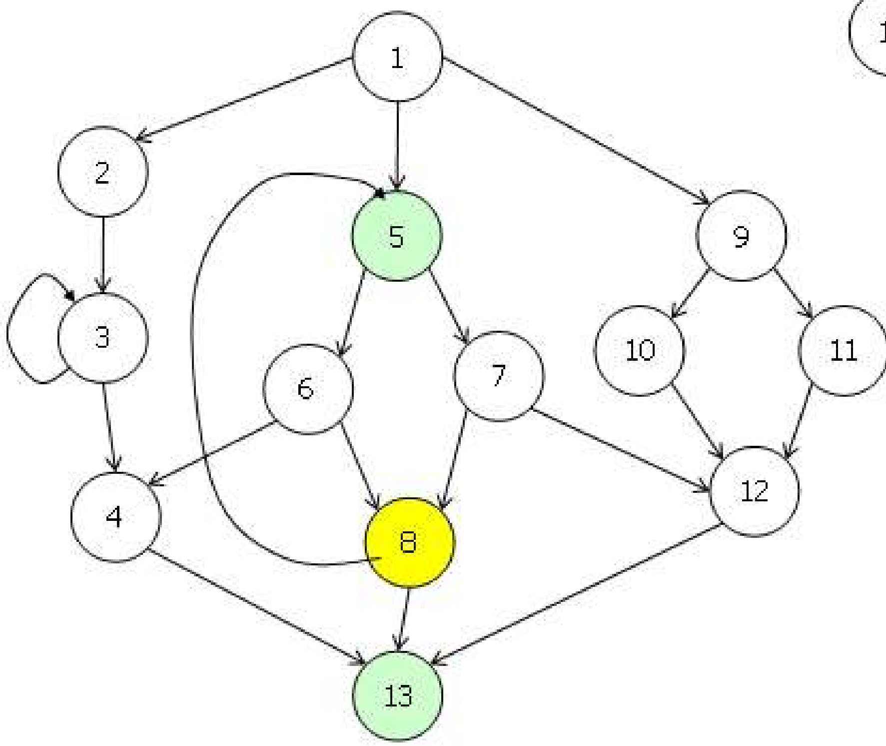

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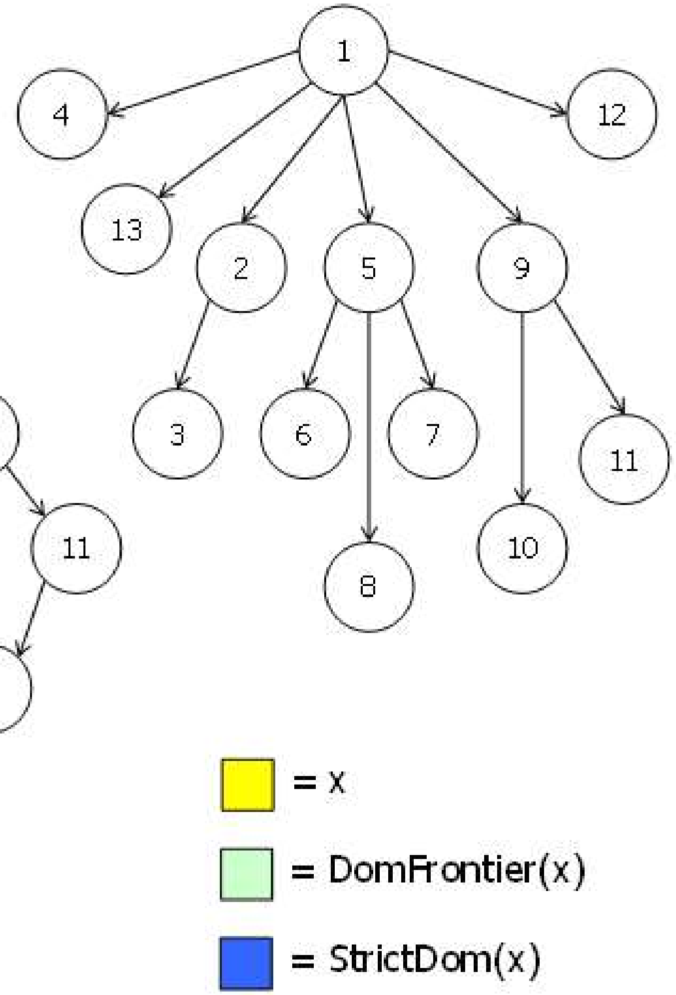

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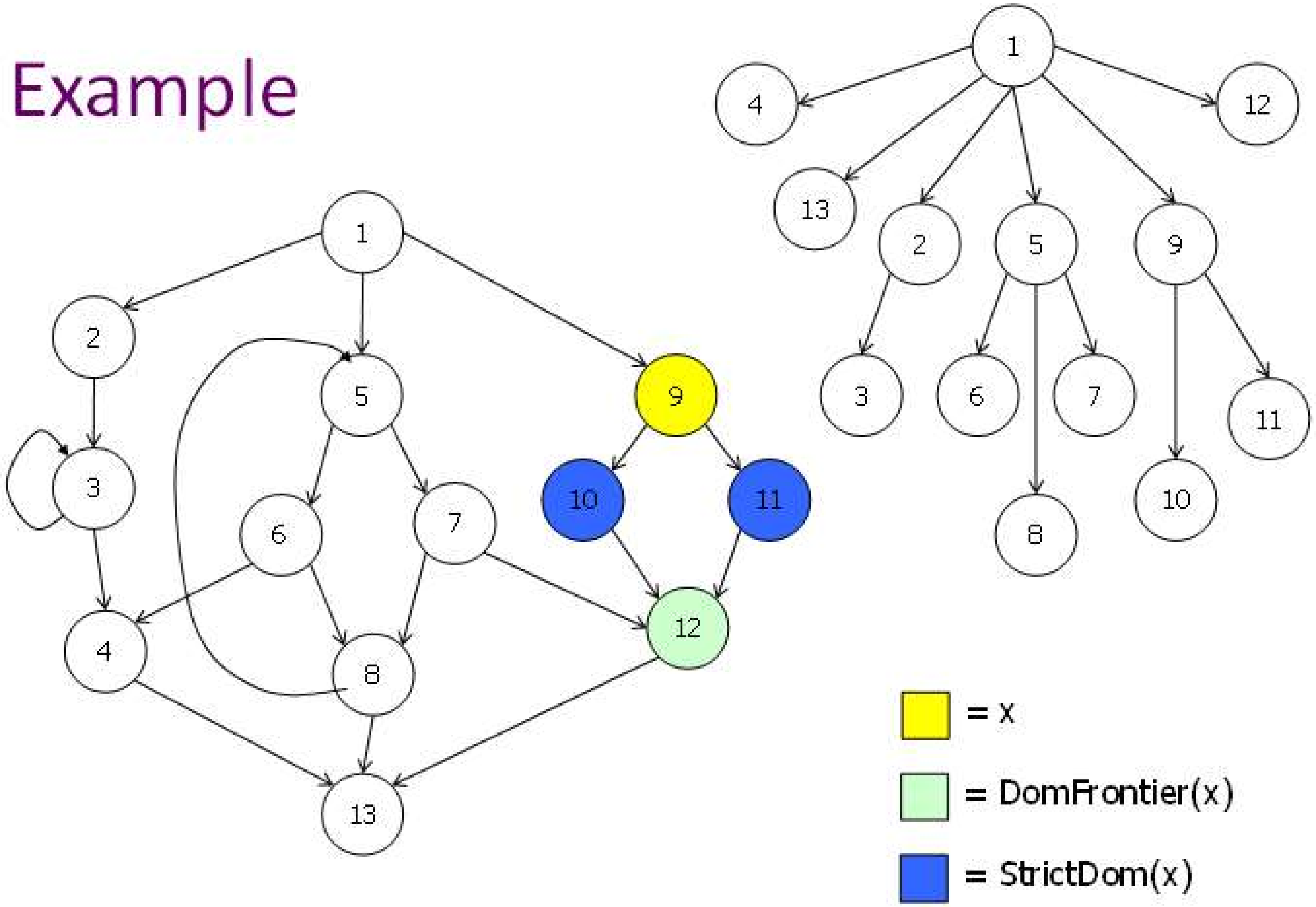

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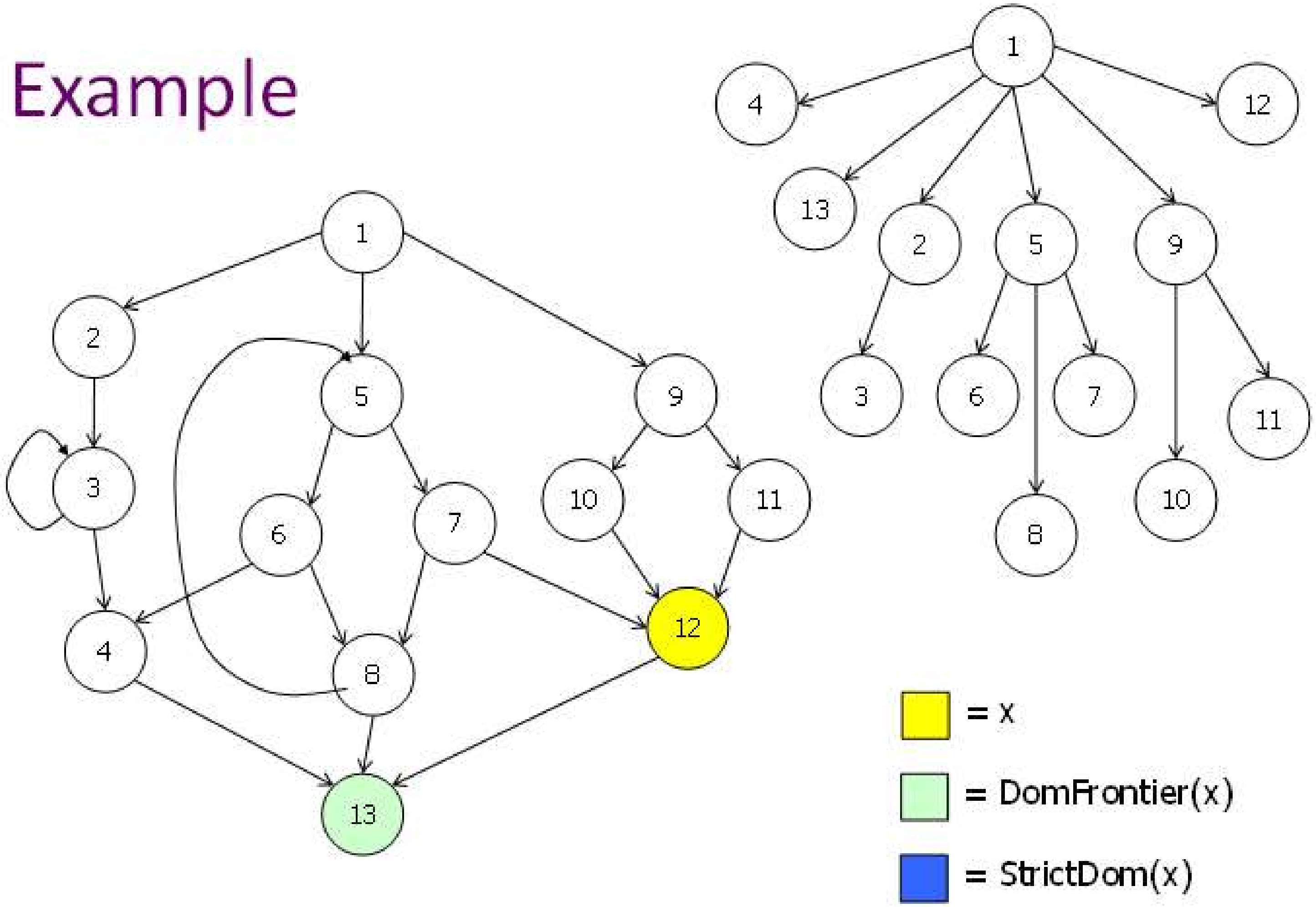
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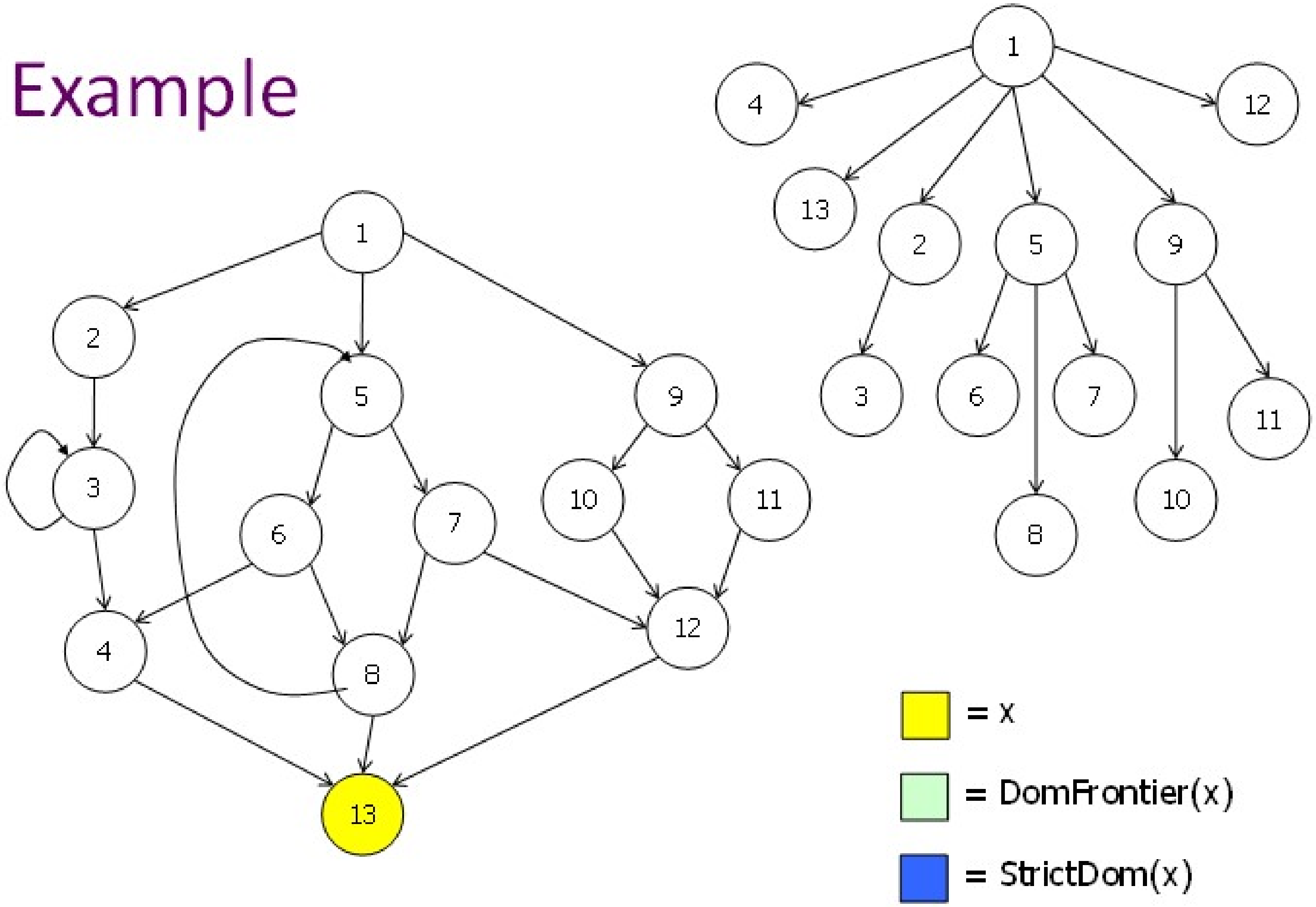
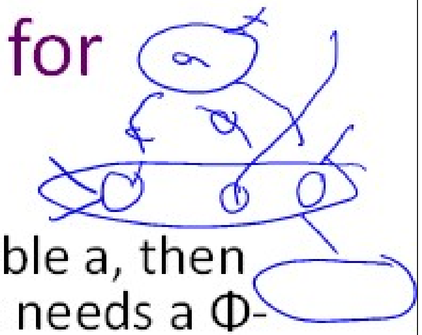


Dominance Frontier Criterion for Placing Φ-Functions



- If a node x contains the definition of variable a, then every node in the dominance frontier of x needs a Φ-function for a
  - Idea: Everything dominated by x will see x's definition of a. The dominance frontier represents the first nodes we could have reached via an alternative path, which *will* have an alternate reaching definition (recall that the entry node defines everything)
    - Why is this right for loops? Hint: strict dominance…
  - Since the Φ-function itself is a definition, this placement rule needs to be iterated until it reaches a fixed-point
- Theorem: this algorithm places exactly the same set of Φ-functions as the path criterion given previously

Placing Φ-Functions: Details

- See the book for the full construction, but the basic steps are:
  1. Compute the dominance frontiers for each node in the flowgraph
  2. Insert just enough Φ-functions to satisfy the criterion. Use a worklist algorithm to avoid reexamining nodes unnecessarily
  3. Walk the dominator tree and rename the different definitions of each variable a to be a_1, a_2, a_3, …

Efficient Dominator Tree Computation

- Goal: SSA makes optimizing compilers faster since we can find definitions/uses without expensive bit-vector algorithms
- So, need to be able to compute SSA form quickly
- Computation of SSA from dominator trees are efficient, but…

Lengauer-Tarjan Algorithm

- Iterative set-based algorithm for finding dominator trees is slow in worst case
- Lengauer-Tarjan is near linear time
  - Uses depth-first spanning tree from start node of control flow graph
  - See books for details

SSA Optimizations

- Why go to the trouble of translating to SSA?
- The advantage of SSA is that it makes many optimizations and analyses simpler and more efficient
  - We'll give a couple of examples
- But first, what do we know? (i.e., what information is kept in the SSA graph?)

SSA Data Structures

- Statement: links to containing block, next and previous statements, variables defined, variables used.
- Variable: link to its (single) definition and (possibly multiple) use sites
- Block: List of contained statements, ordered list of predecessors, successor(s)

Dead-Code Elimination

$v = a \ op \ b$

- A variable is live ⇔ its list of uses is not empty(!)
  - That's it! Nothing further to compute
- Algorithm to delete dead code:

```
while there is some variable v with no uses
    if the statement that defines v has no
            other side effects, then delete it
```

  - Need to remove this statement from the list of uses for its operand variables – which may cause those variables to become dead

Simple Constant Propagation

- If c is a constant in v := c, any use of v can be replaced by c
  - Then update every use of v to use constant c
- If the c_i's in v := $\Phi(c_1, c_2, \ldots, c_n)$ are all the same constant c, we can replace this with v := c
- Incorporate copy propagation, constant folding, and others in the same worklist algorithm

Simple Constant Propagation

W := list of all statements in SSA program
while W is not empty
  remove some statement S from W
  if S is v:=Φ(c, c, ..., c), replace S with v:=c
  if S is v:=c
    delete S from the program
    for each statement T that uses v
      substitute c for v in T
      add T to W

Converting Back from SSA

- Unfortunately, real machines do not include a Φ instruction
- So after analysis, optimization, and transformation, need to convert back to a "Φ-less" form for execution

Translating Φ-functions

$x_i := a$ $\quad$ $x_j := b$ $\quad$ $x_k := c$

$x = a$ $\quad$ $x = b$ $\quad$ $x = c$

$\cancel{x \leftarrow \Phi(\ )}$

- The meaning of $x := \Phi(x_1, x_2, \ldots, x_n)$ is "set $x{:=}x_1$ if arriving on edge 1, set $x{:=}x_2$ if arriving on edge 2, etc."
- So, for each i, insert $x := x_i$ at the end of predecessor block i
- Rely on copy propagation and coalescing in register allocation to eliminate redundant copy instructions

SSA Wrapup

- More details needed to fully and efficiently implement SSA, but these are the main ideas
  - See recent compiler books (but not the Dragon book!)
- Allows efficient implementation of many optimizations
- SSA is used in most modern optimizing compilers (llvm is based on it) and has been retrofitted into many older ones (gcc is a well-known example)
- Not a silver bullet – some optimizations still need non-SSA forms, but very effective for many