Slicing Modern Program Structures While Eliminating Irrelevant Loops

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Kansas State University

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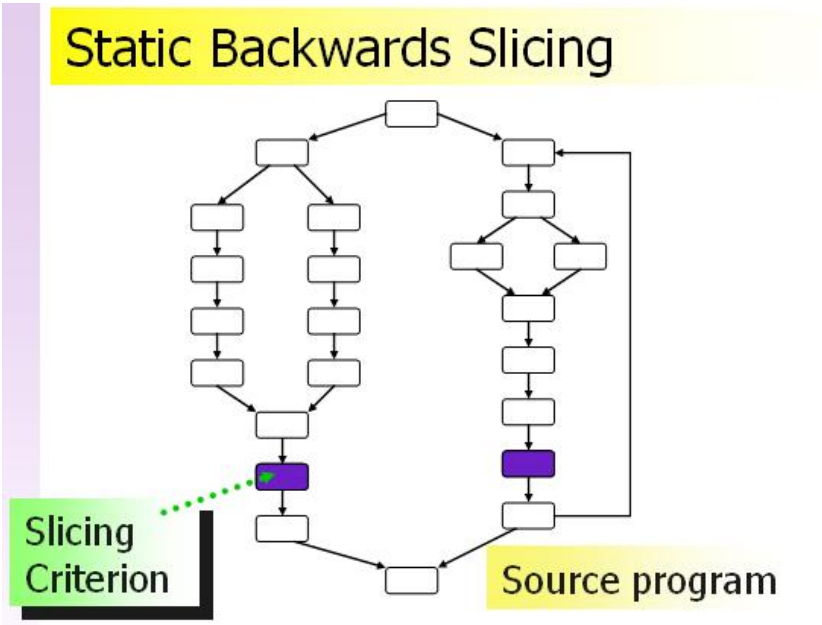
What is Slicing?



Pick one or more program points of interest (called the slicing criterion)

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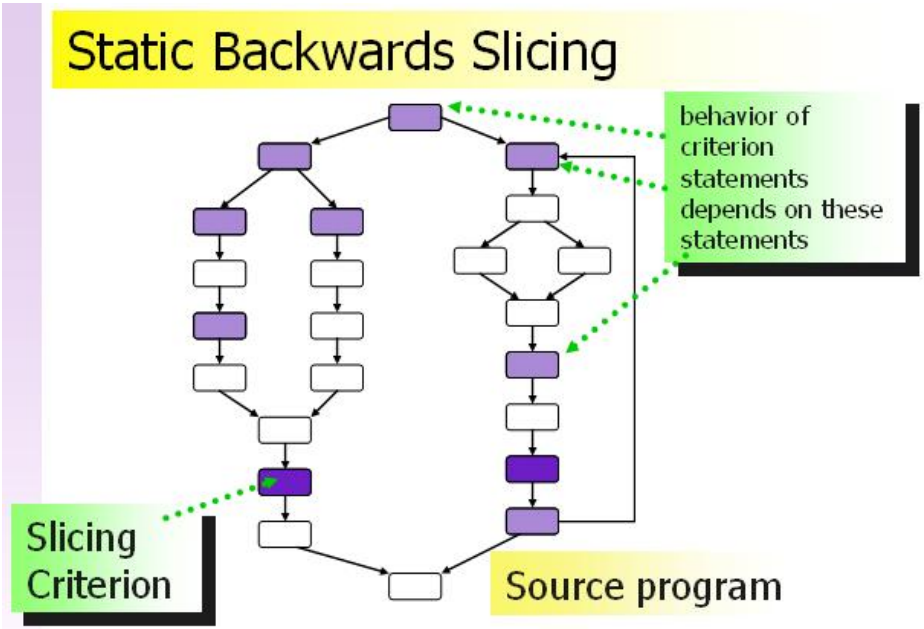

Walk backwards to find nodes that C depend on (called the slice set)

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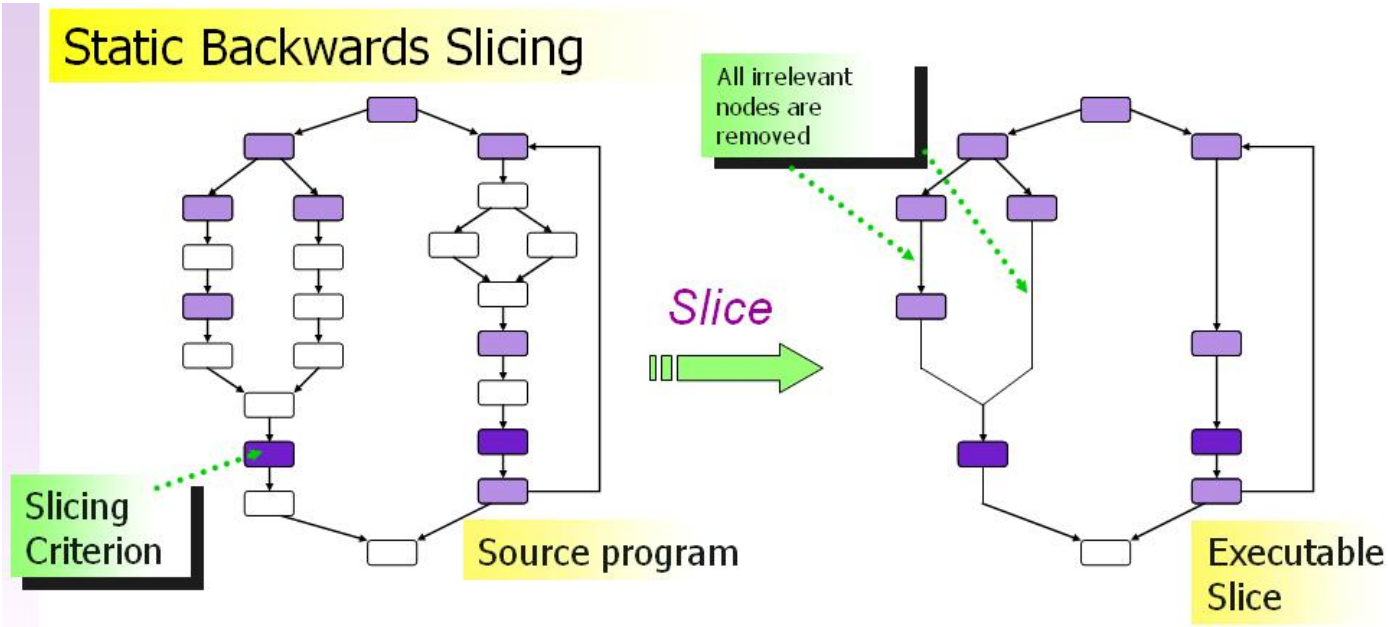

Remove irrelevant nodes
(or replace them by dummy nodes)

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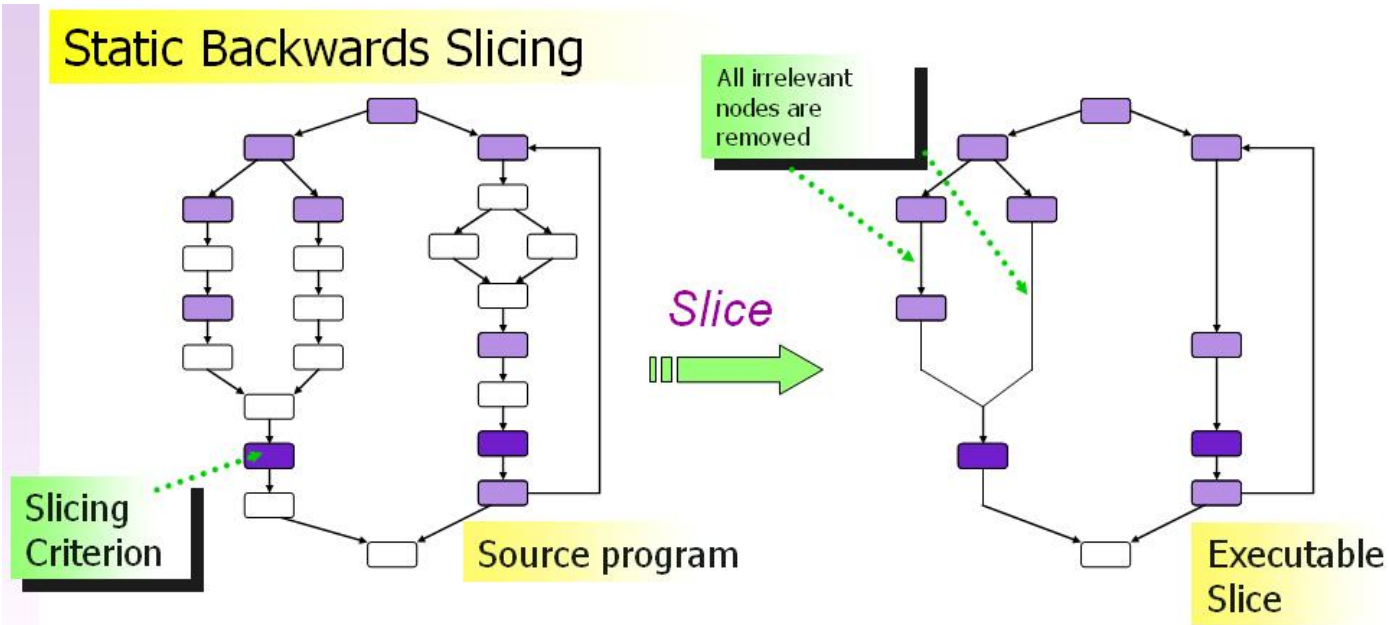

Applications include

- compiler optimizations
- debugging
- model checking
- protocol understanding

Challenge

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- the observable behavior of source program is prefix of observable behavior of sliced program.

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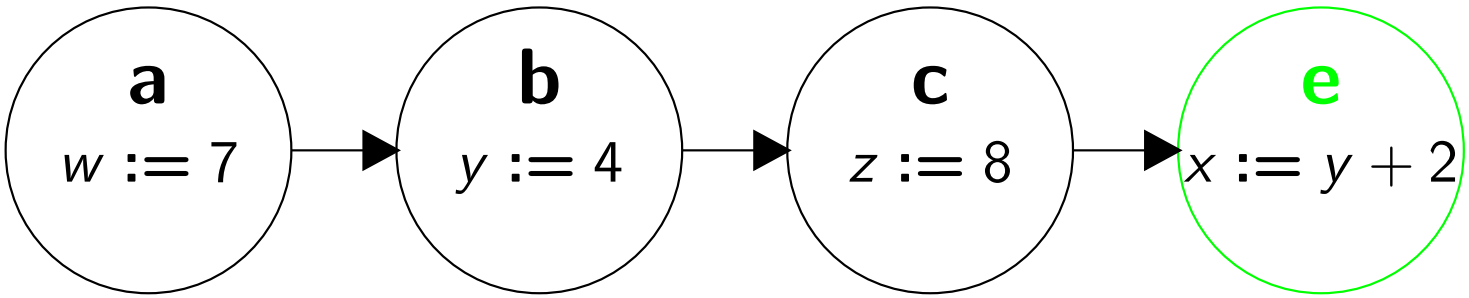
- this is expressed using simulation
- correctness proof easily fits conference page limits

Data Dependence

Source: final value of $x = 6$



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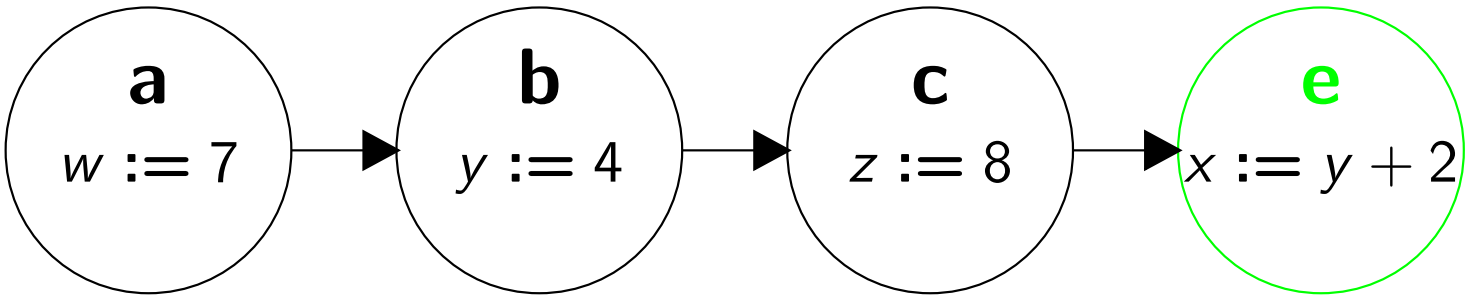

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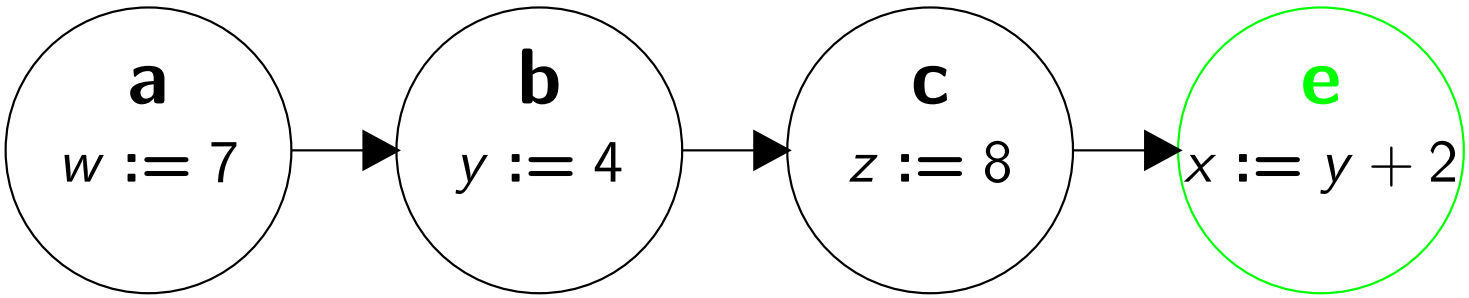

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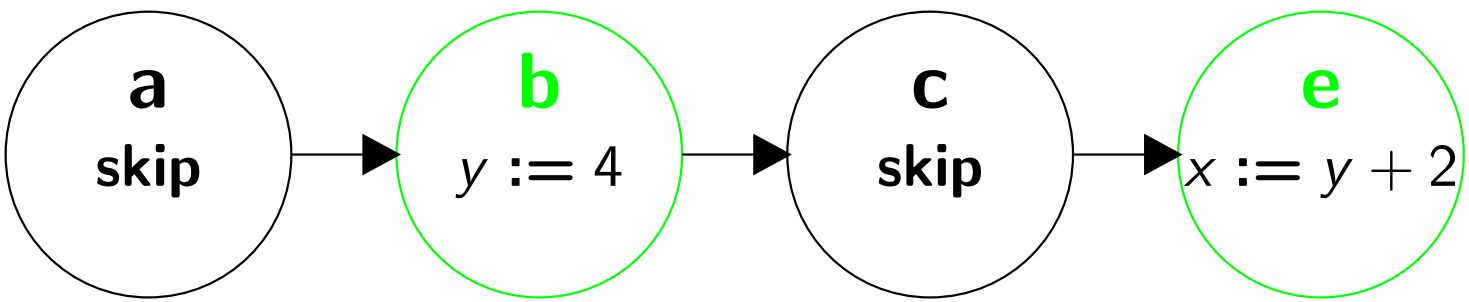

Control Dependence (CD)

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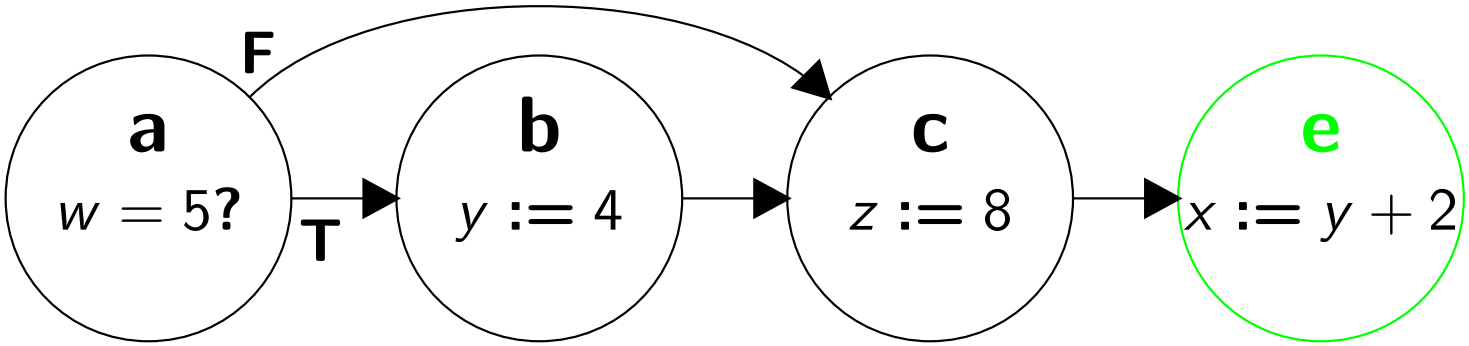

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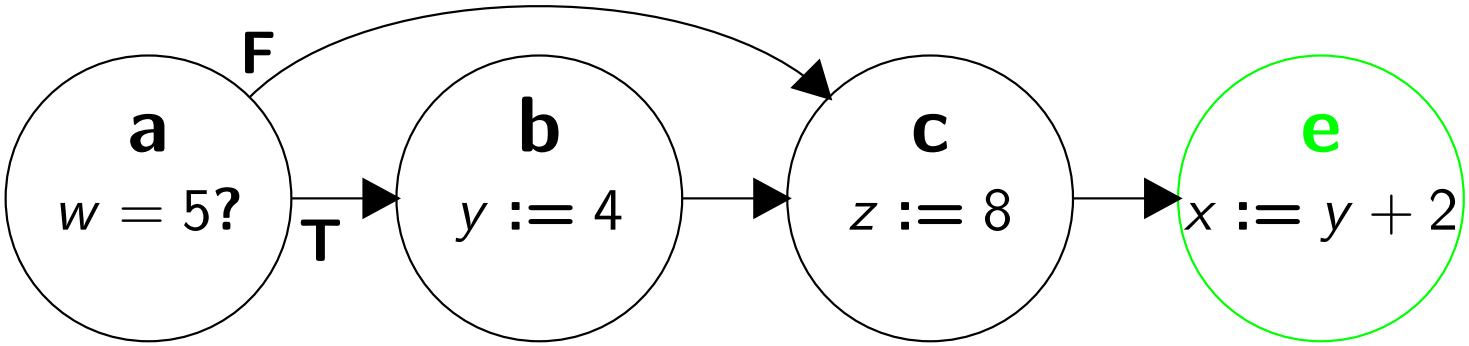

$b \xrightarrow{dd} e$ and b is control dependent on a, $a \xrightarrow{cd} b$, since

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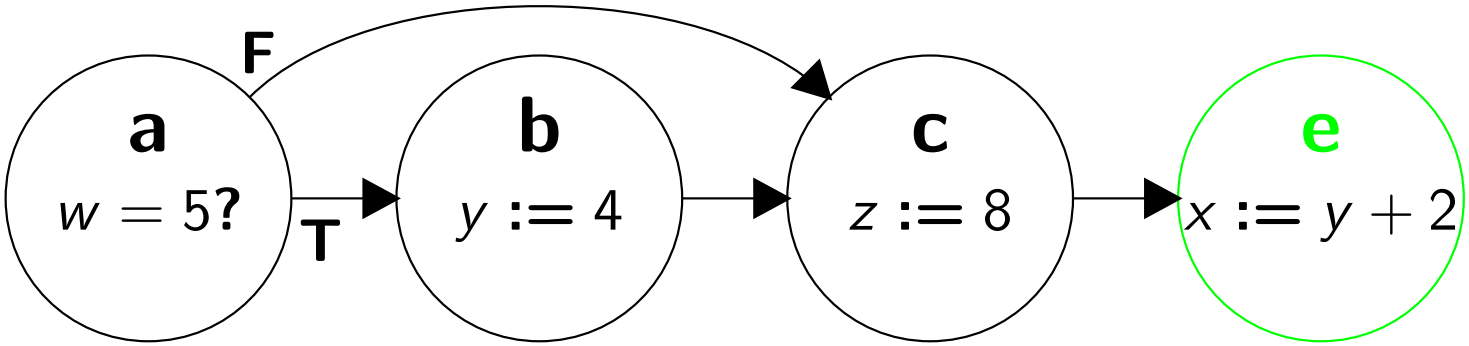

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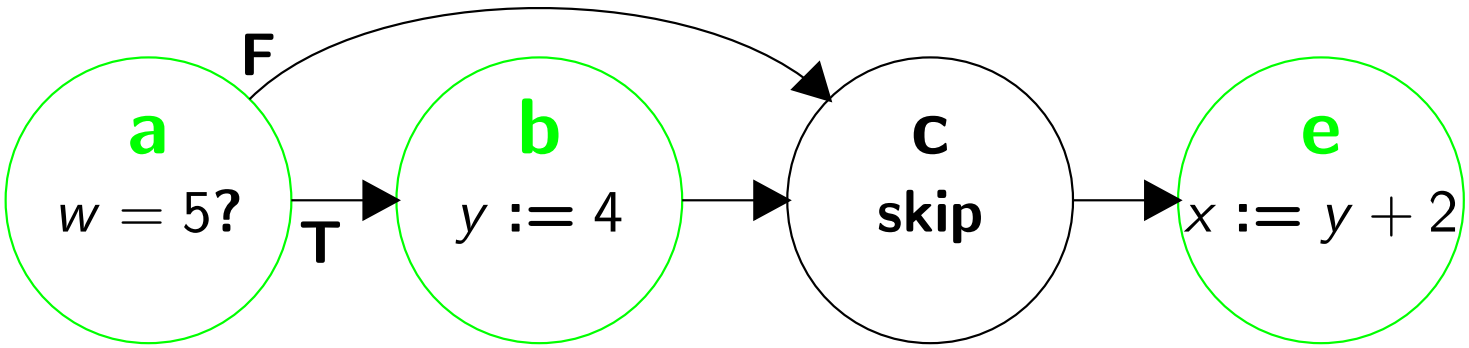

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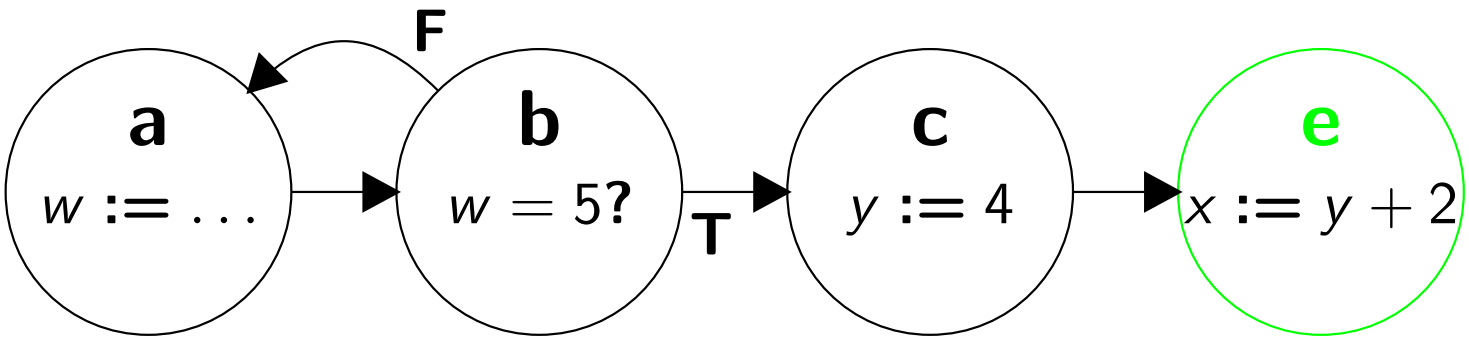

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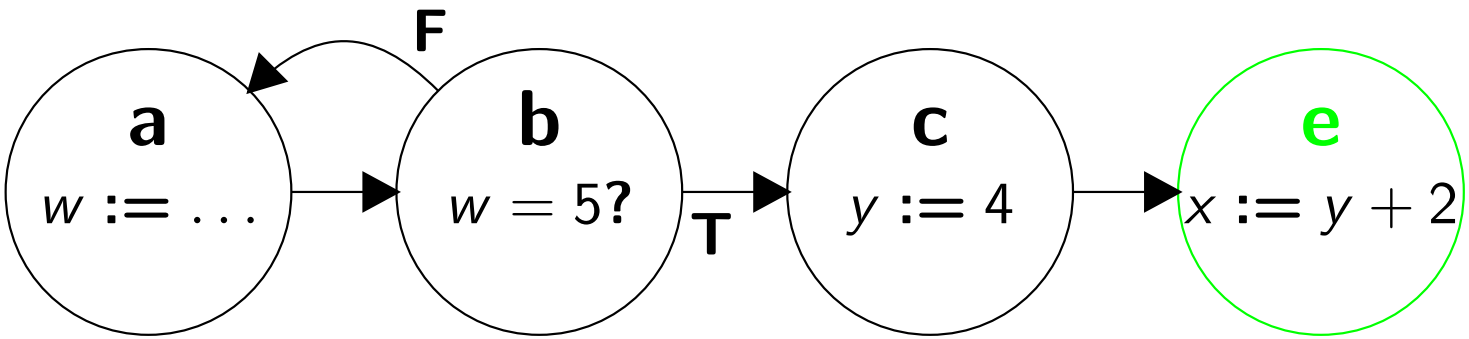

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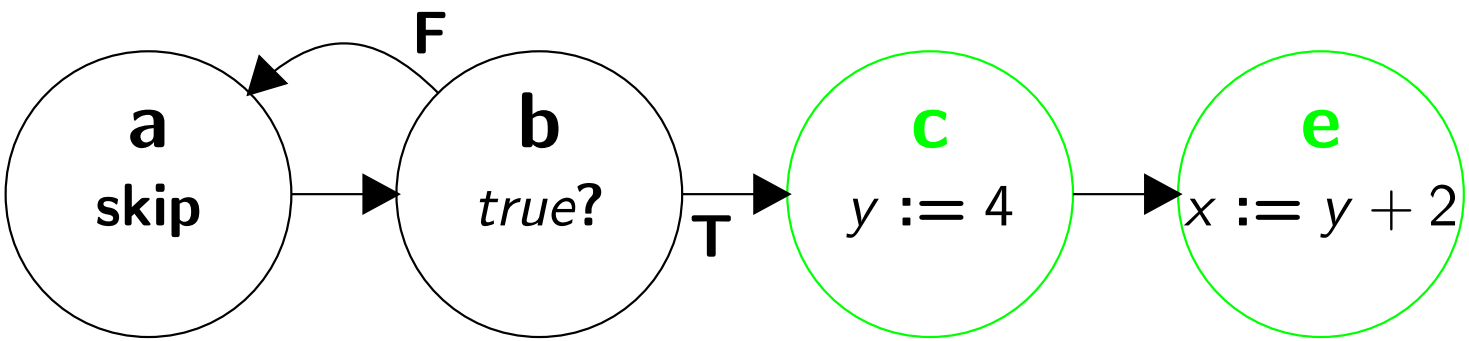

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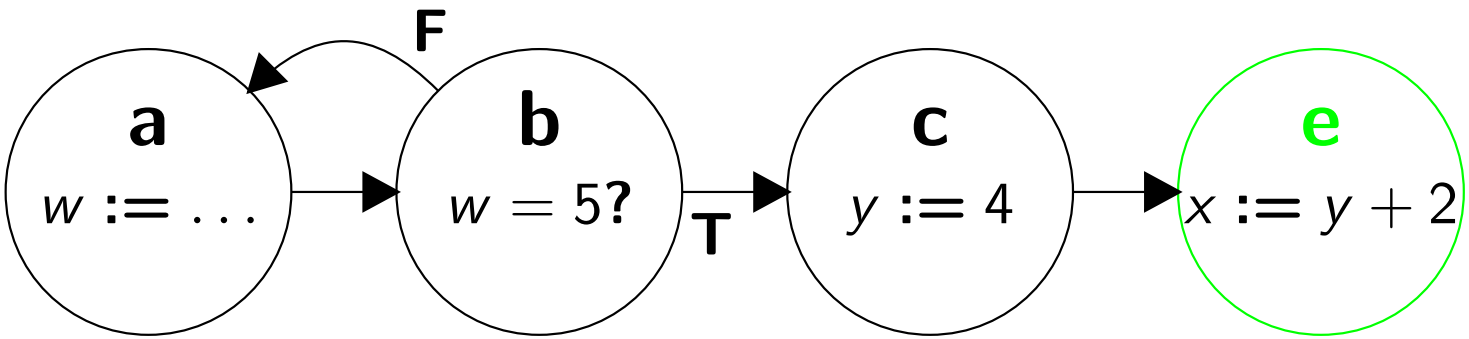

$c \xrightarrow{dd} e$ but $b \not\xrightarrow{cd} c$, since c strictly postdominates b

But c is weakly control dependent on b, $b \xrightarrow{wcd} c$ (though no $[b..e]$ bypasses c, b may cause indefinite delay of c)

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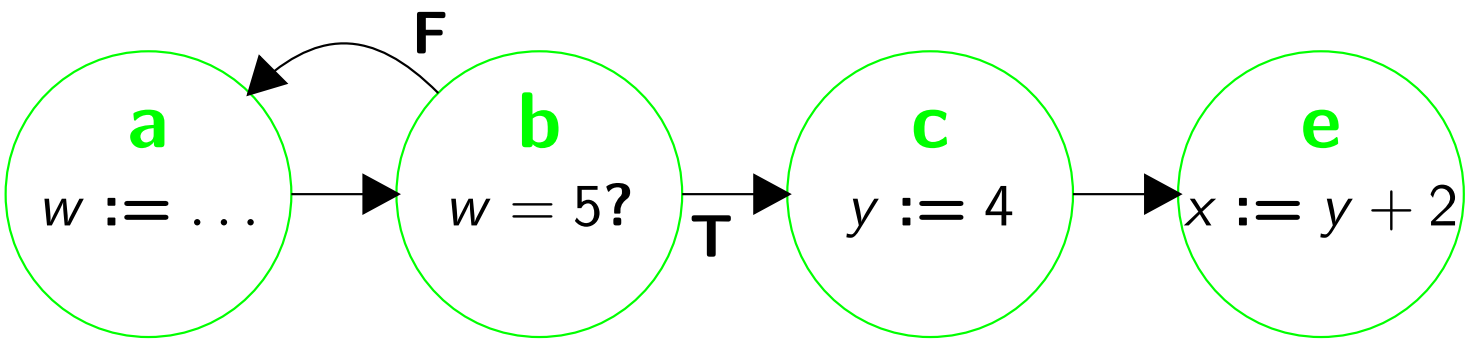

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- The definitions so far assume the existence of a (unique) end node.
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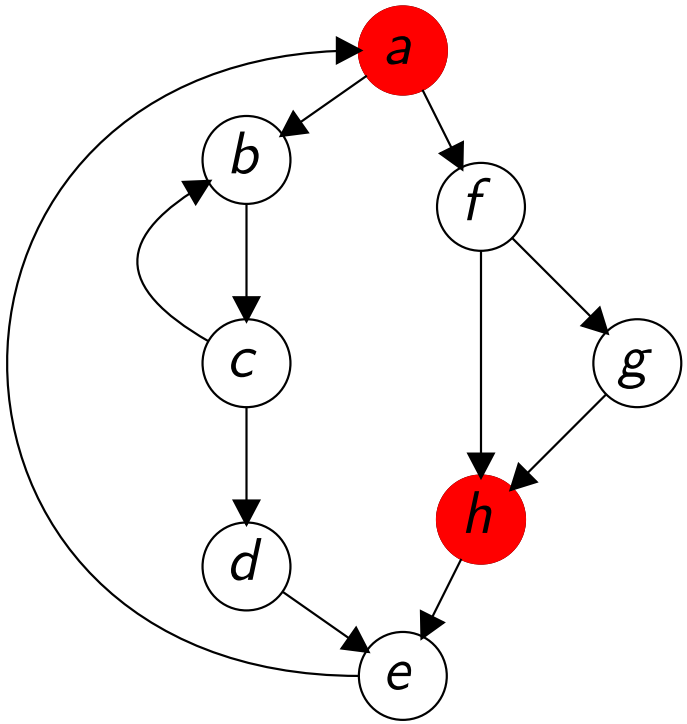
This is called NTSCD (non-termination sensitive CD)

- Conservative Extension: in the special case where the CFG has an end node, NTSCD is equivalent to Podgurski & Clarke's weak control dependence.

Illustrating NTSCD

h NTSCD on a



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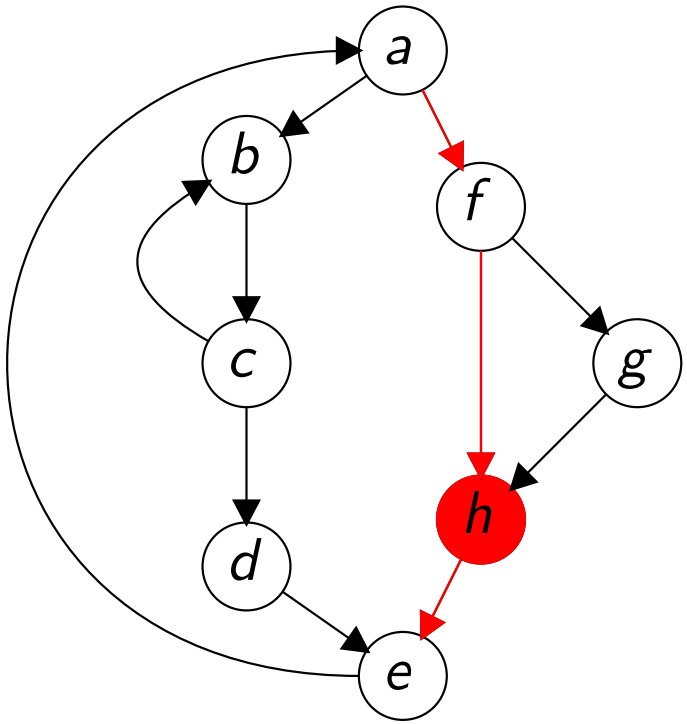

If a selects f then h cannot be avoided

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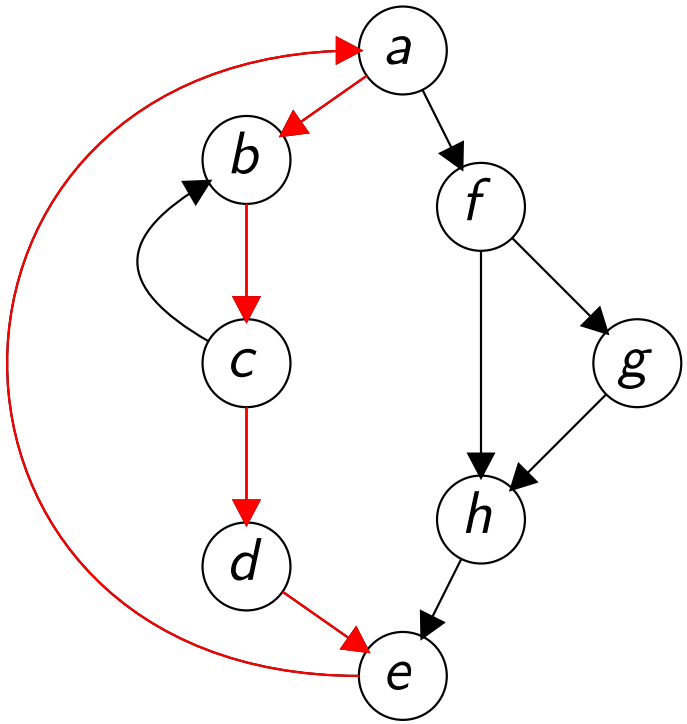
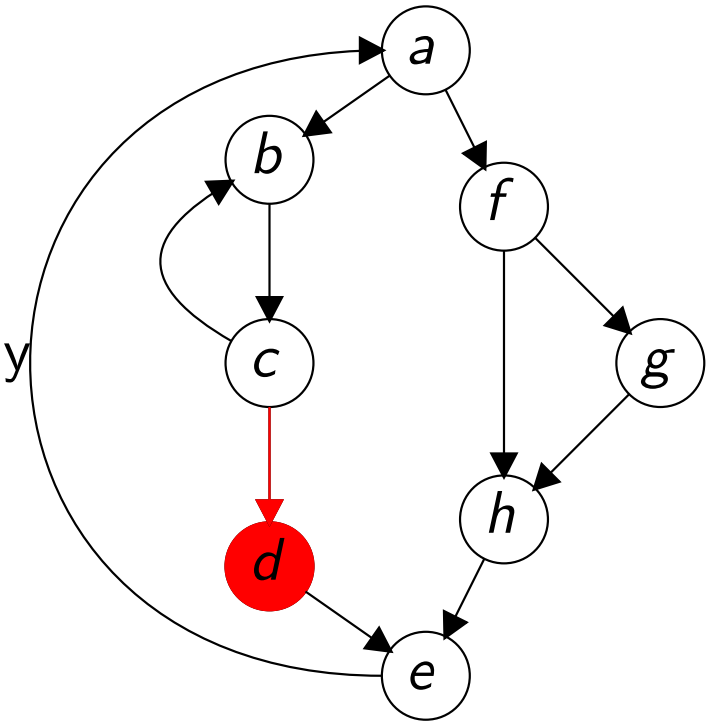


If a selects b then h can be avoided forever

Illustrating NTSCD

Termination is Preserved

d NTSD on c
so inner loop not sliced away



If c selects d then d cannot be avoided

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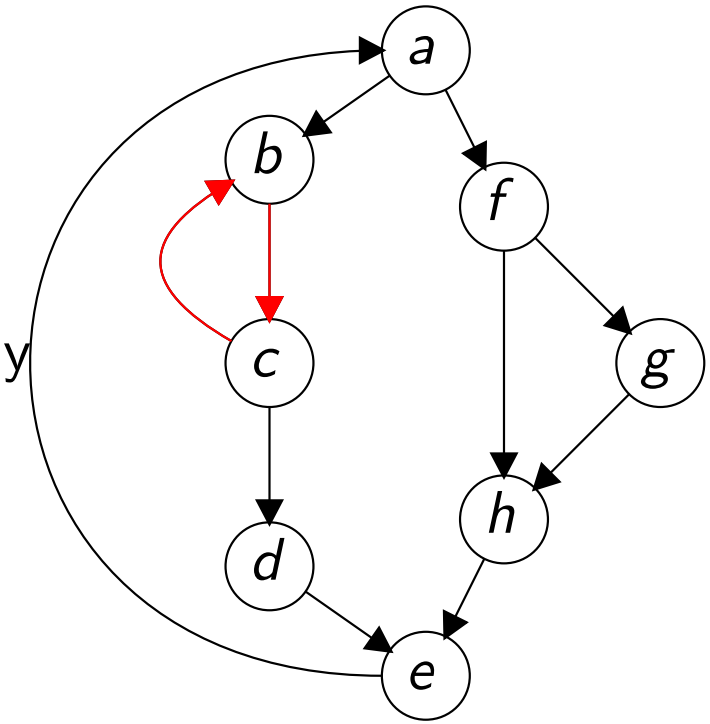

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Correctness of NTSCD

We aim at (weak) bisimulation:

- if a node can do an observable action in the source program, it can do so in the sliced program
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- Also, for stores to be bisimilar, they must agree on "relevant" variables.

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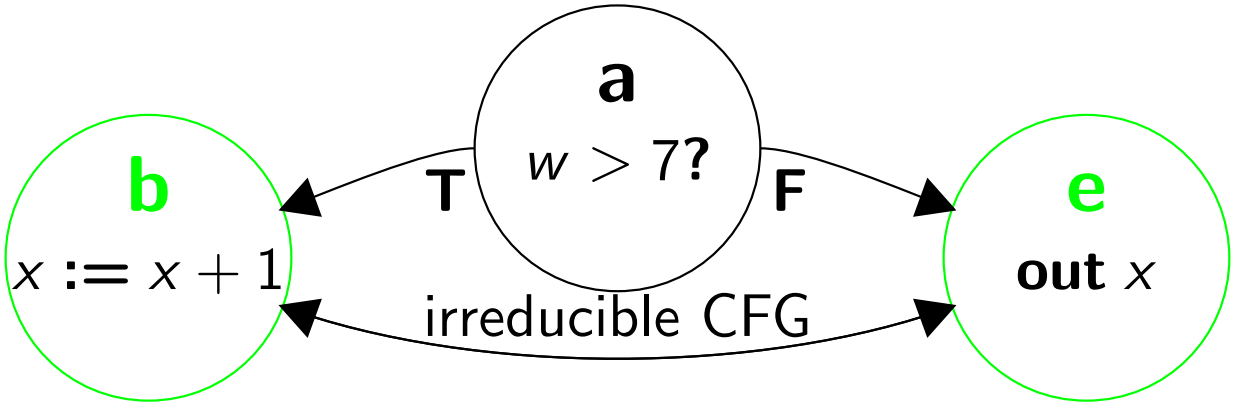
If the CFG is reducible, we can prove that slicing based on NTSCD gives rise to a bisimulation. Recall that a CFG is reducible if its edges can be split into

- forward edges which form a DAG;
- back edges where the target dominates the source

Irreducible Graphs



Observable behavior: 1,2,3,. . . if $w > 7$, else 0,1,2,. . .

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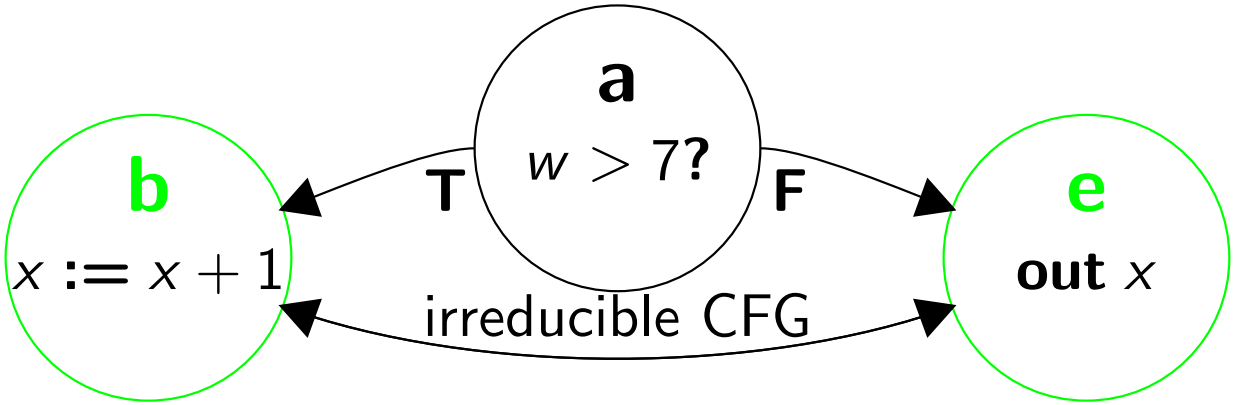

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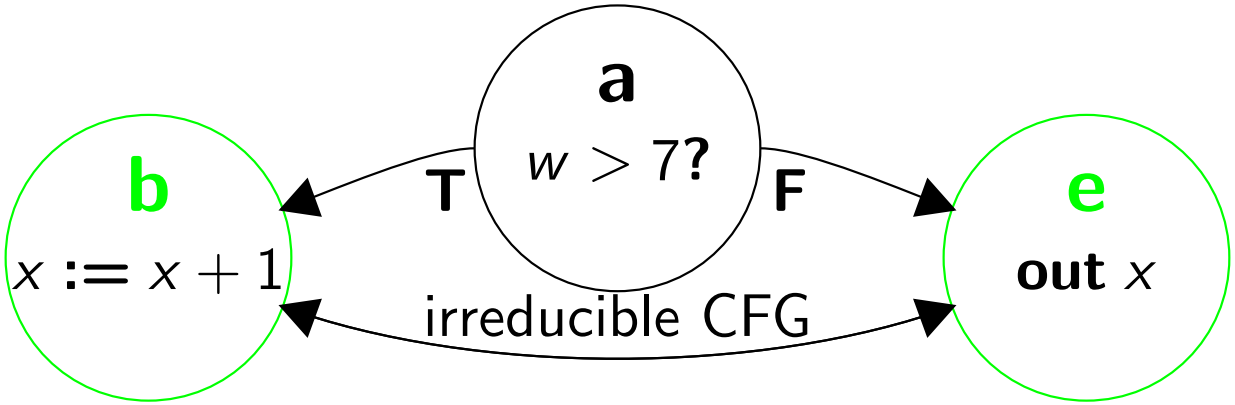

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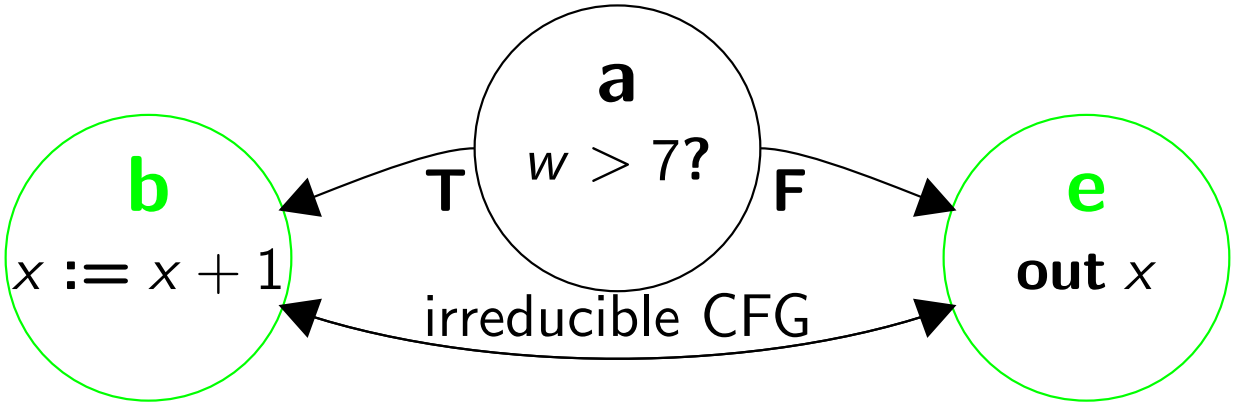

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Theorem For an arbitrary CFG (with/without end nodes, reducible or not), the sliced program is bisimular to the source program, provided the slice set is closed under

- data dependency
- NTSCD
- a certain kind of "order dependency"

Assessment

The approach by Ranganath et al

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We may like to discard nodes that may influence loops if they do not impact observable computation

- thus we should generalize $\stackrel{cd}{\longrightarrow}$ rather than $\stackrel{wcd}{\longrightarrow}$
- as was done by something called NTICD, but which was not helpful to establish the correctness of slicing

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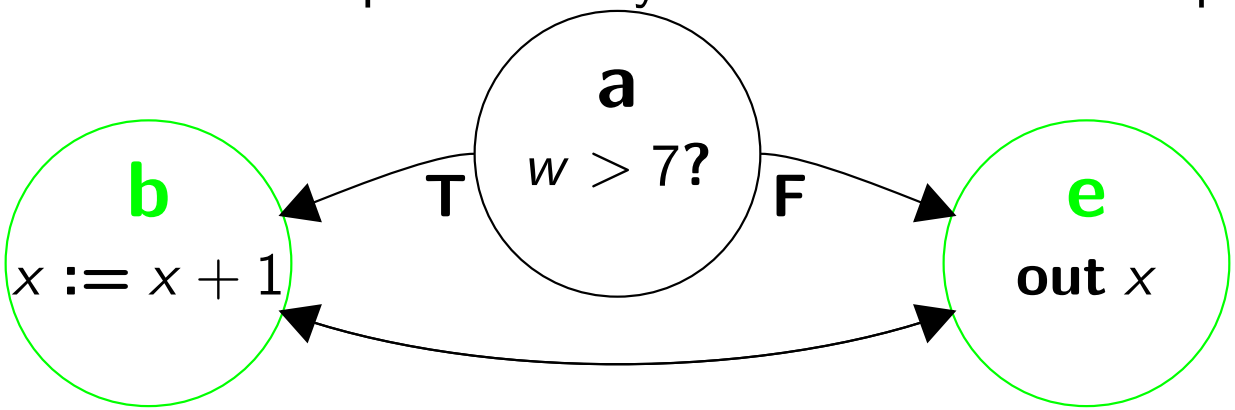

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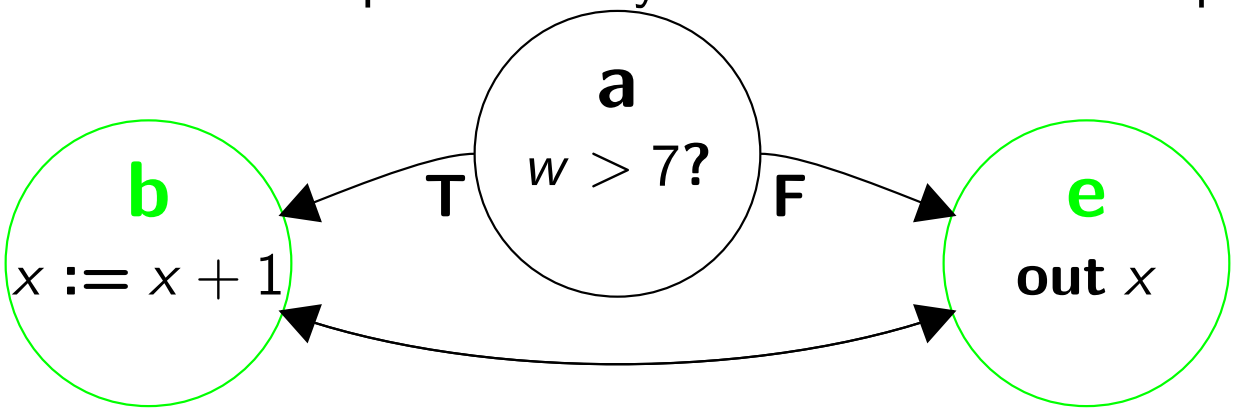

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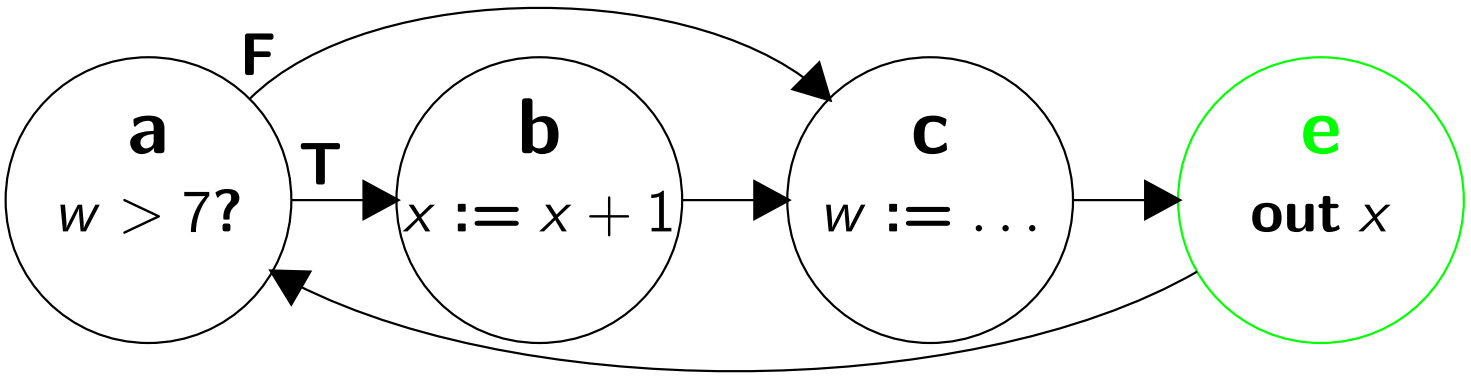
We shall see that $\overset{wod}{\longrightarrow}$, though ternary, subsumes standard control dependency.

Example: WOD for Conditionals

Source: observable behavior of the form
1,1,2,2,2,3,4,4,. . .



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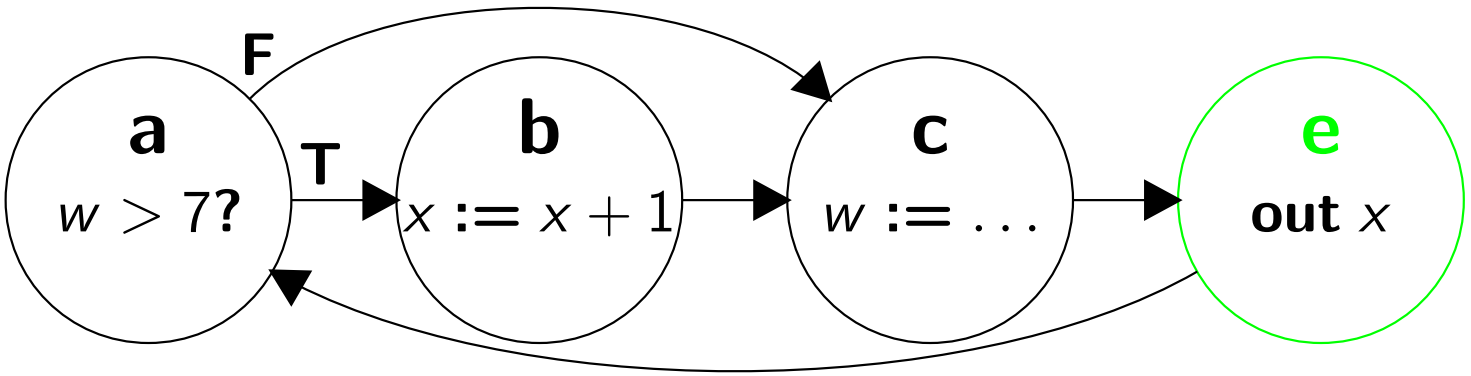

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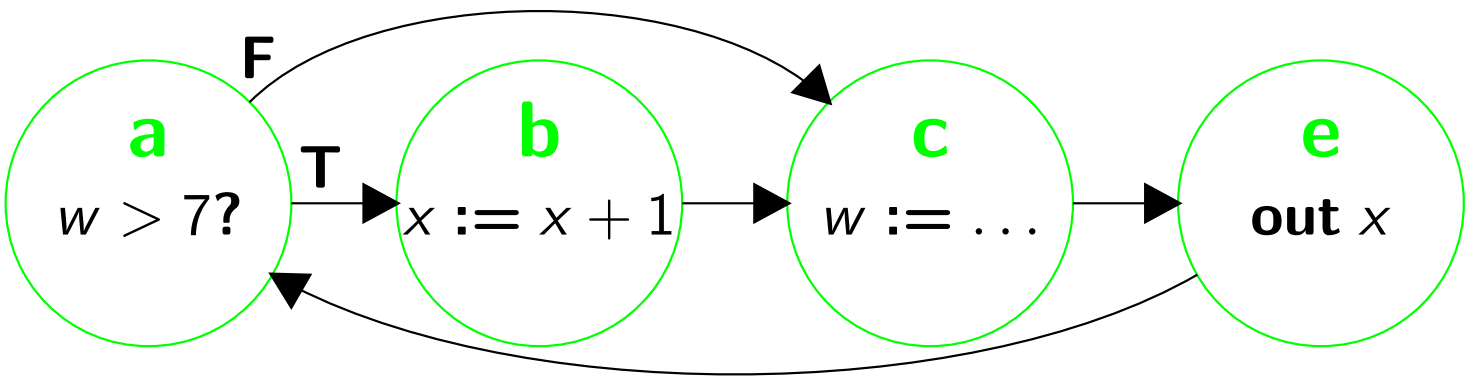

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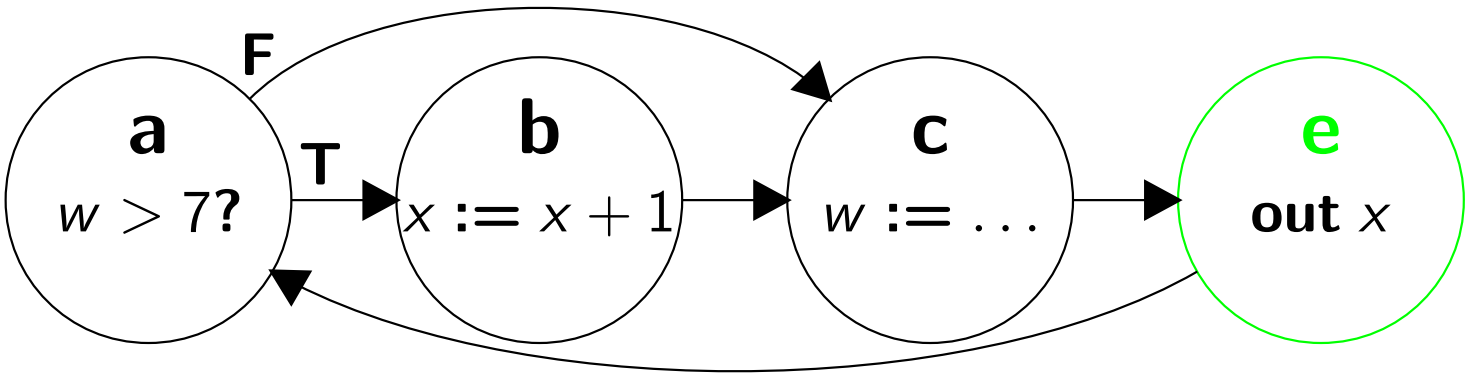

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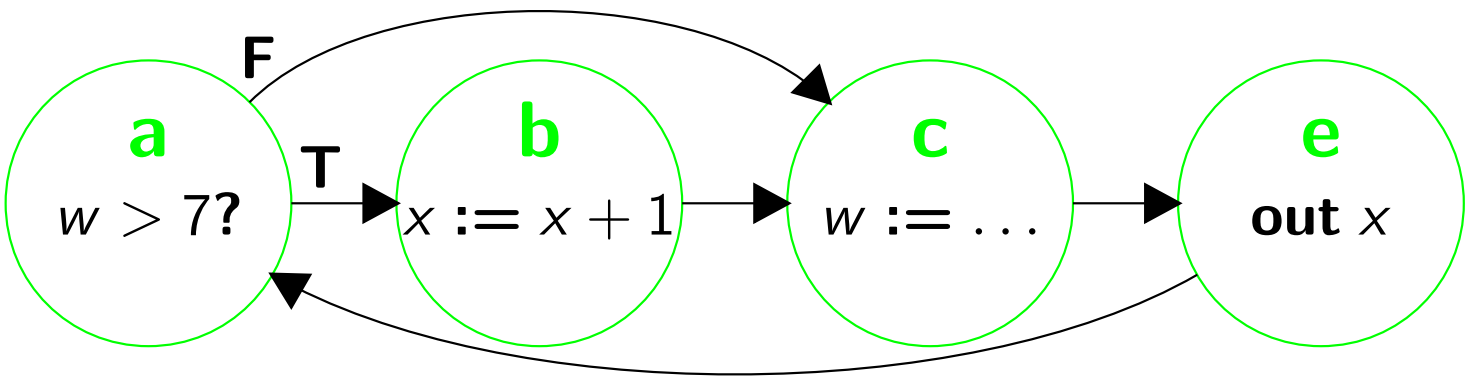

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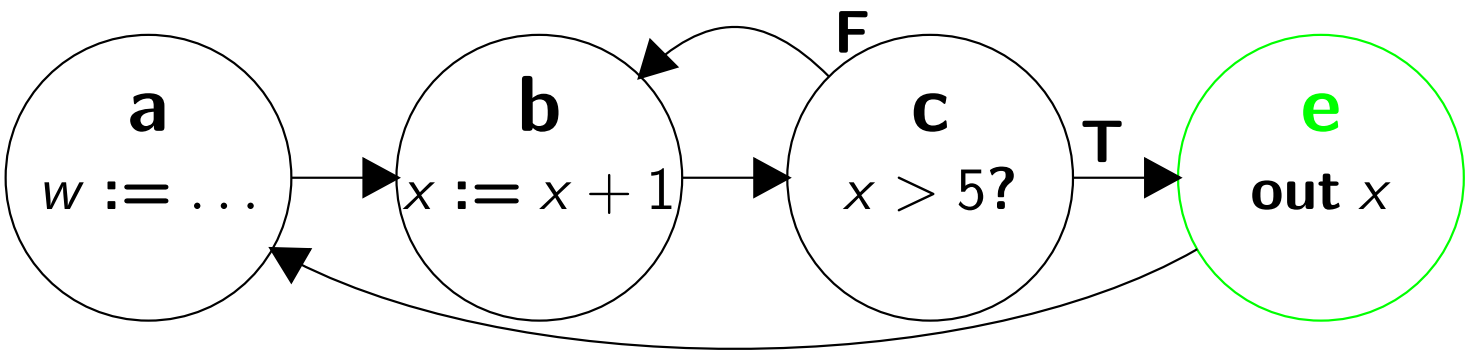

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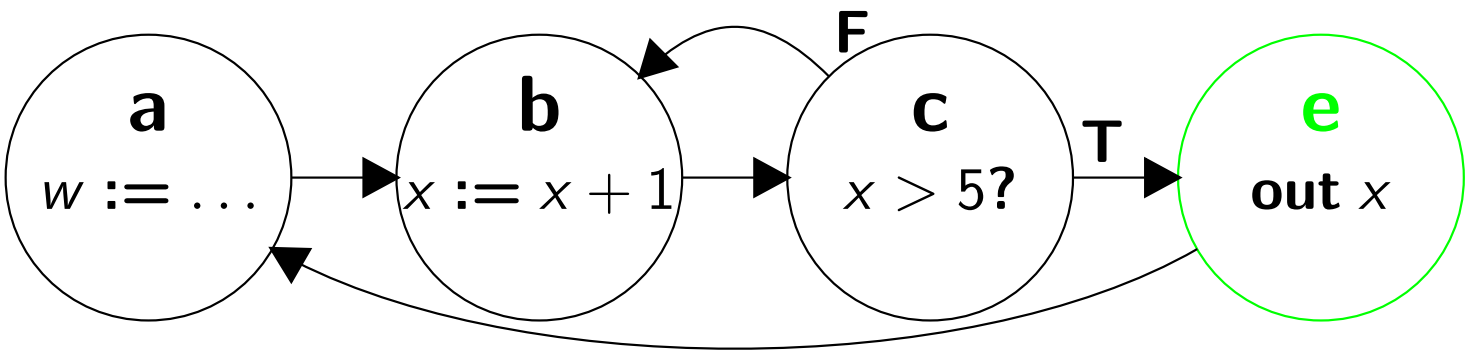
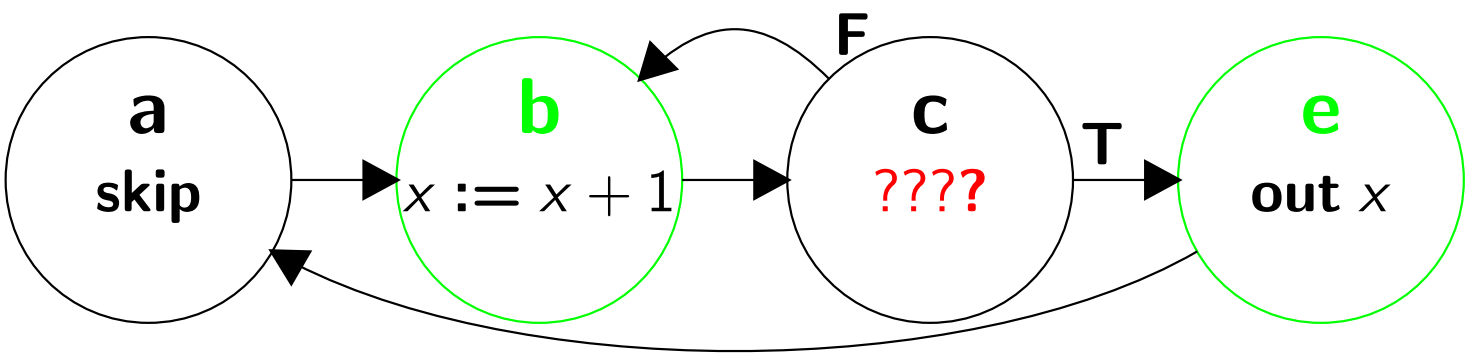


Slice: observable behavior if guard wrongly sliced away:

- 1,2,3,4,5,... if replaced by *true*
- ϵ if replaced by *false*



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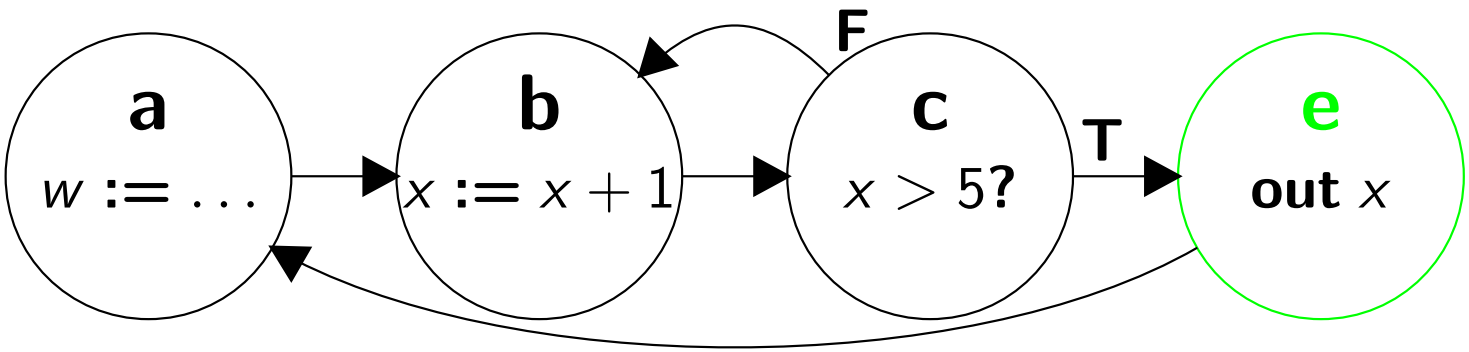
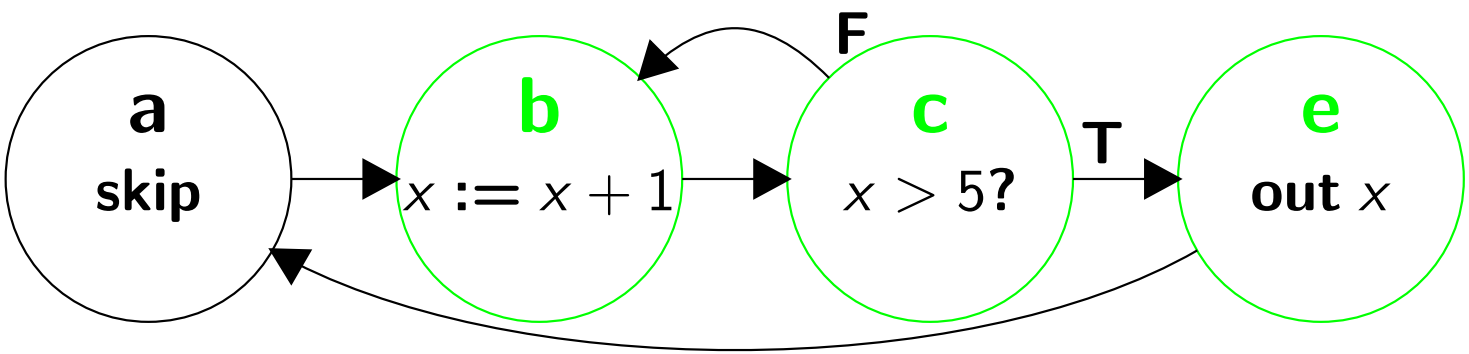


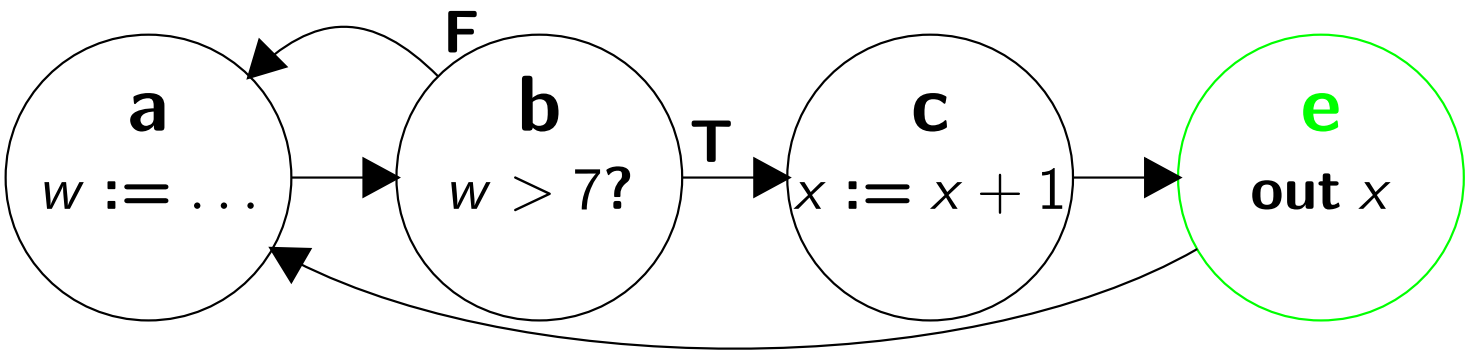
$c \overset{wod}{\rightarrow} b, e$ since

- path $[c..b] \not\ni e$ and path $[c..e] \not\ni b$
- c has successor b with $[b..b]$ and all $[b..e]$ contain b



Example: WOD for Irrelevant Loops

Source: observable behavior 1,2,3,4,. . . or prefix thereof



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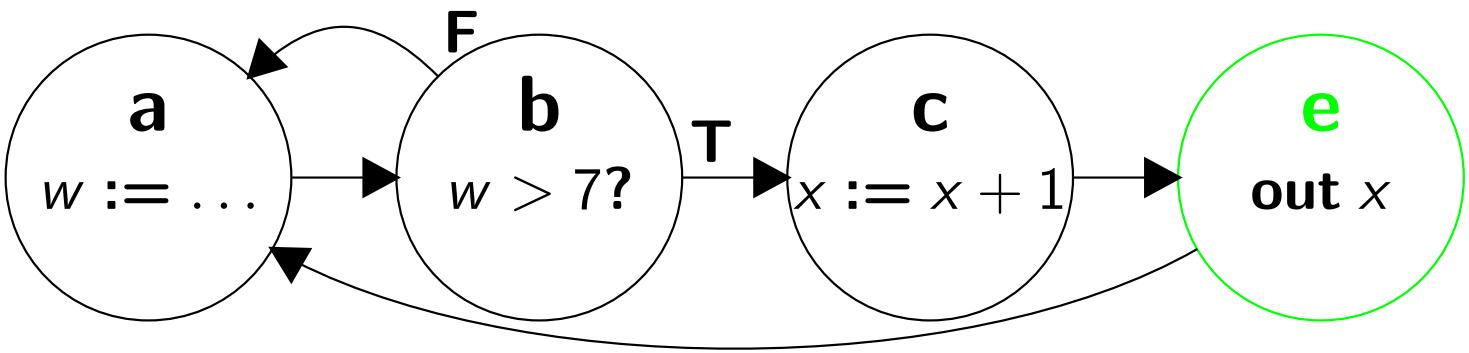
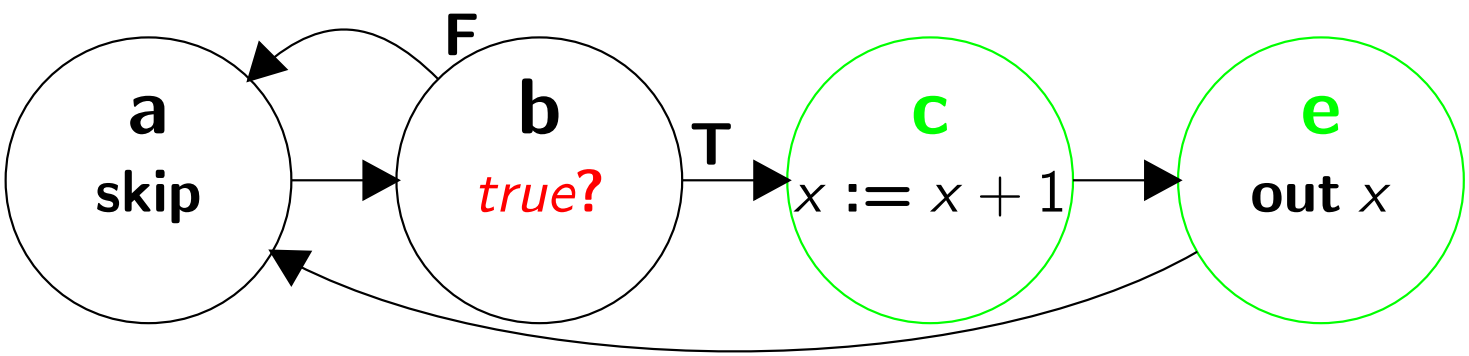


New guard chosen to get closer to next observable.
Slice: observable behavior 1,2,3,4,. . .



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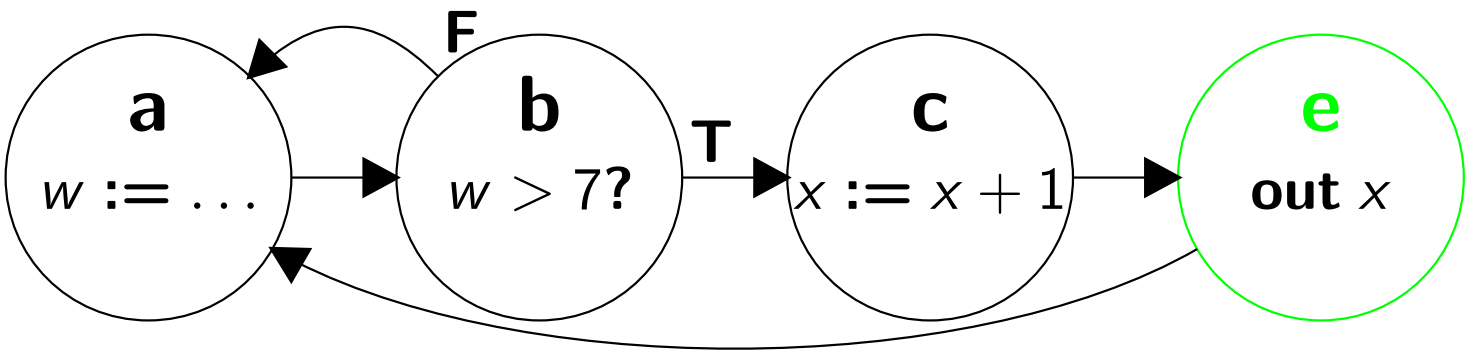

$b \overset{wod}{\not\mapsto} c, e$ since

- no path $[b..e] \not\ni c$

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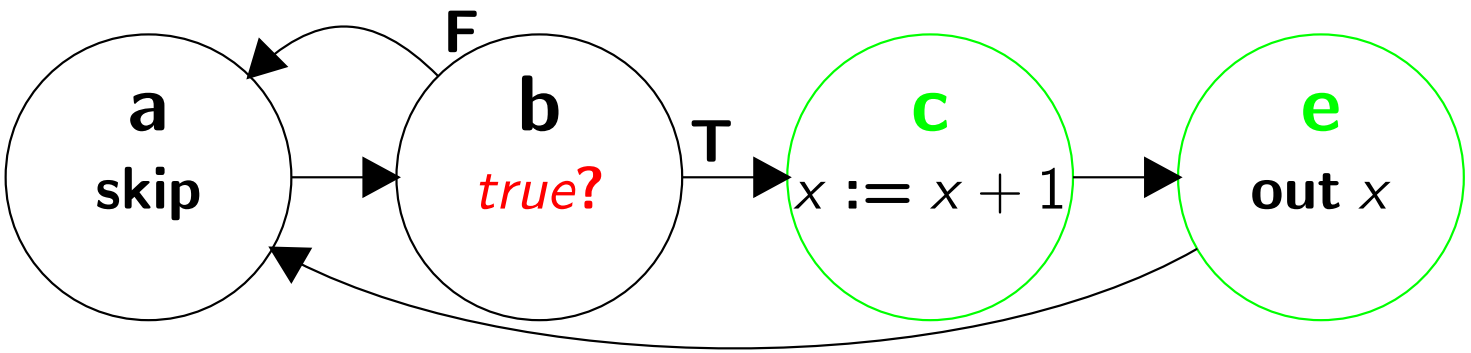

Relating WOD to CD

Conservative extension For a CFG with an end node which is part of slicing criterion, the closures of $\overset{wod}{\longrightarrow}$ and $\overset{cd}{\longrightarrow}$ coincide.

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  - $a \overset{cd}{\longrightarrow} b$ in $G_{\rightarrow c}$, or
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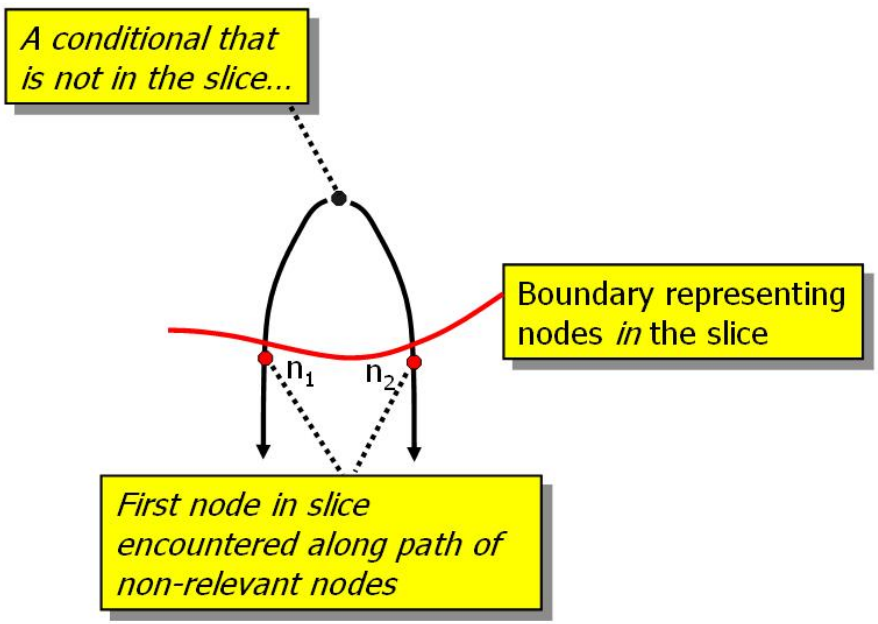
- if $a \overset{cd}{\longrightarrow} c$ in $G_{\rightarrow b}$ with $a \neq c$ then $a \overset{wod}{\longrightarrow} b, c$ in G.

Unique Next Observable

- For the correctness proof, we shall assume the set of observables is closed under $\overset{dd}{\longrightarrow}$ and $\overset{wod}{\longrightarrow}$.
- Key advantage of being closed under $\overset{wod}{\longrightarrow}$: at most one next observable.



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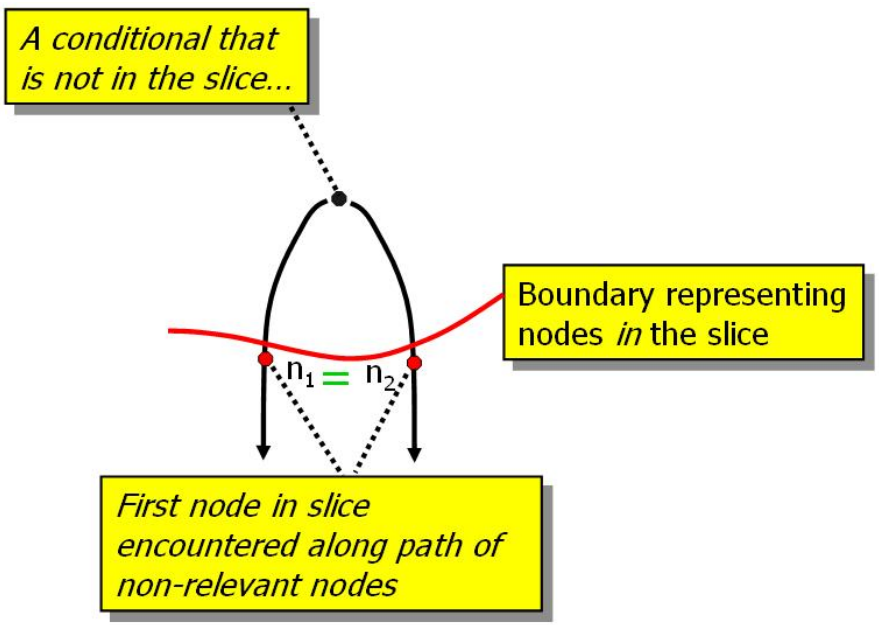

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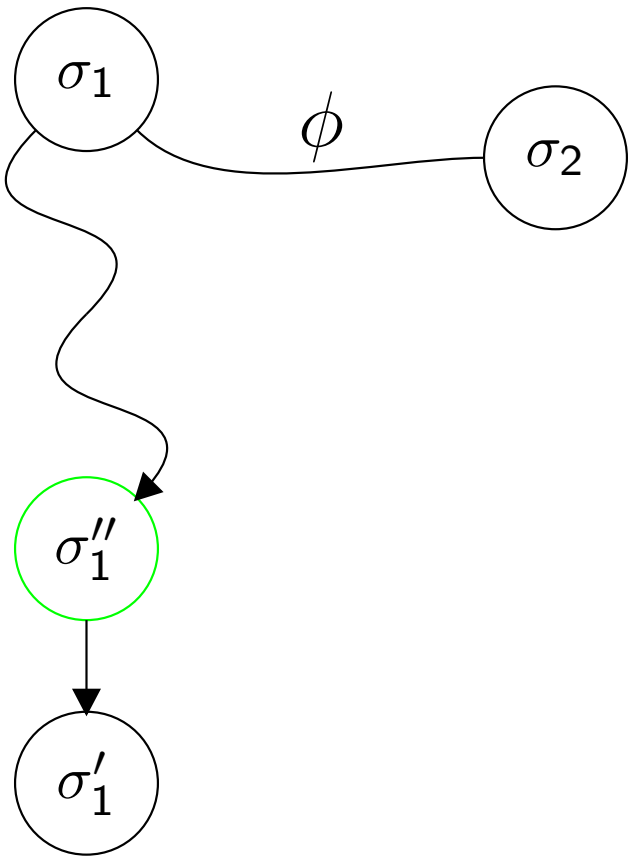
Recent classification [Sebastian Danicic]: all slices in the literature computes one of the two below:

- the least set where all nodes have at most one next observable.
  This is weak commitment, as computed by $\overset{cd}{\longrightarrow}$, and for general CFGs by $\overset{wod}{\longrightarrow}$.
- the least set where all nodes have at most one next observable, and satisfy that all nodes either
  - eventually will reach an observable, or
  - always avoids an observable

  This is strong commitment, as computed by $\overset{wcd}{\longrightarrow}$, and for general CFGs by $\overset{ntscd}{\longrightarrow} + \overset{\text{“}dod\text{”}}{\longrightarrow}$.

Weak Simulation

- Slicing Correctness expressed using weak simulation
- A weak simulation relates source states to slice states
- A program state is an node and a store



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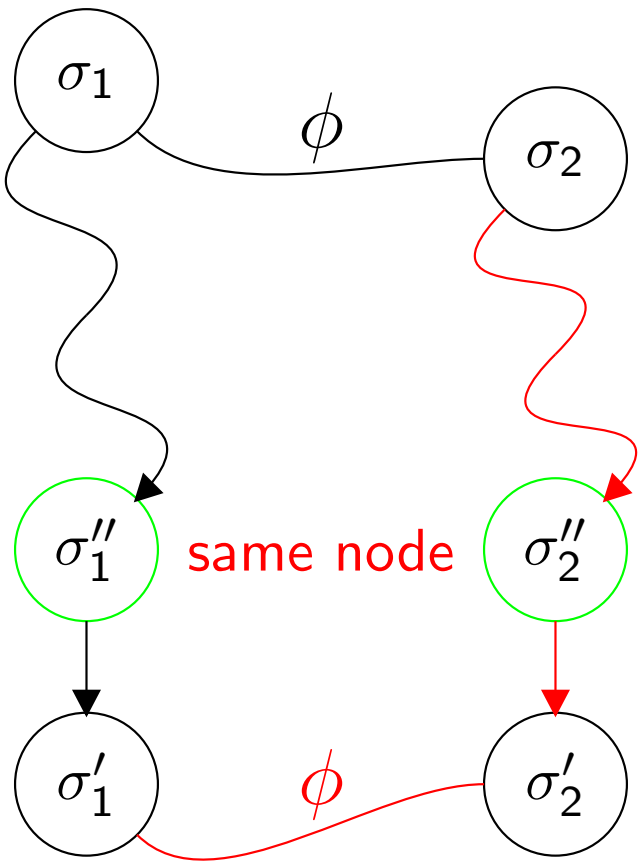

Relevant Variables

A variable x is relevant at n if

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Facts:

- this definition is independent of whether one considers the source or the slice
- if two nodes have the same next observable, they have the same relevant variables

Defining a Concrete Weak Simulation

We define $(n_1, \sigma_1)\ R\ (n_2, \sigma_2)$ if

- n_1 and n_2 have the same next observable
- σ_1 and σ_2 agree on the relevant variables

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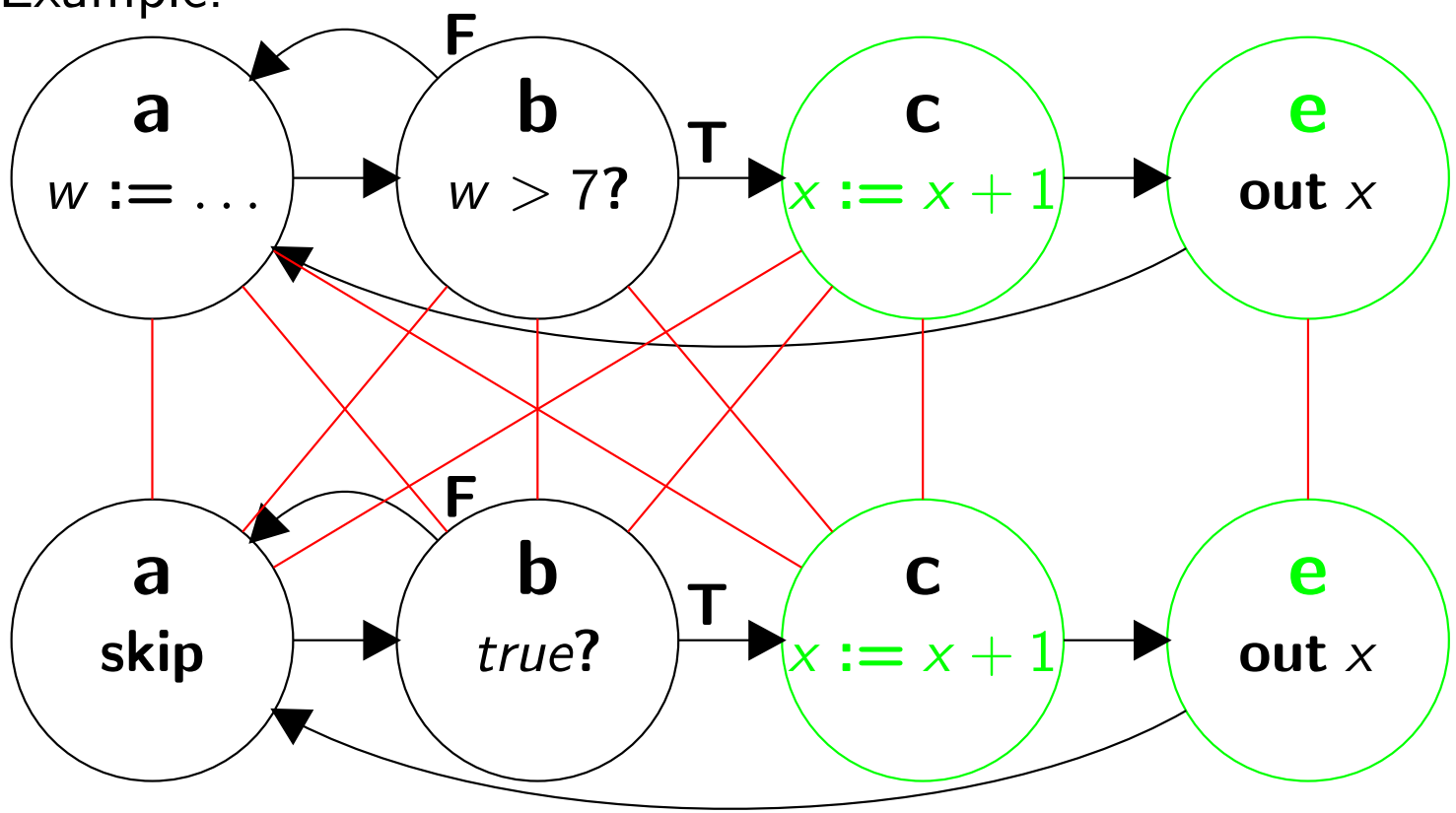
Example:



Correctness

Theorem

- R is a weak simulation.

Thus any observable action by the source can be matched by the slice, but not necessarily vice versa.

Related Work

Ball & Horwitz, 1993

- assumes unique end node
- correctness expressed using pointwise history
- one history is allowed to be prefix of other

Hatcliff et al, HOSC 2000

- assumes unique end node
- used for model checking, implying
  - sequencing of observables must be preserved
  - liveness properties must be preserved
- detailed correctness proof, assuming termination of both source and slice

Hatcliff et al, SAS 1999

- considers multi-threading
- proposes bisimulation as correctness property
- does not work out the details

Assessment

Foundation for slicing which

- handles CFGs that arise in modeling reactive systems
- produces manageable slices
- allows crisp correctness proof

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Open question: Is (bi)simulation a strictly stronger correctness criterion than "pointwise" (bi)simulation?

If so, we might modify $\overset{wod}{\longrightarrow}$ to allow for independent assignments to be swapped.

Future Work

- Interprocedural analysis
- Multi-threading
- Connect to information flow analysis (Hammer & Krinke & Snelting)