# Lecture 17

# Flow Analysis

## flow analysis in prolog; applications of flow analysis

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# Today

Static program analysis

- what is it and why do it

Points-to analysis

- static analysis for understanding how pointer values flow

Andersen’s algorithm

- via deduction

Andersen’s algorithm in Prolog

- just four lines

Andersen’s algorithm via CYK parsing (optional)

- CFL-reachability

# Static program analysis

Answers questions about program properties

- related to static type inference

Static analysis == at compile time

- that is, prior to seeing the actual input
- hence, the answer must be correct for all inputs

Sample program properties:

Does var x have a constant value (for all inputs)?

Does foo() return a table (whenever called, on all inputs)?

# Motivation for static program analysis (1)

Optimize the program.

Ex: replace x[i] with x[1] if we know that i is always 1.

Constant propagation

```
i = 2
…
i = i+2
…
if (…) { … }
…
x[i] = x[i-1]
```

Q: is i a constant no matter which side of if is taken?

Q: is i always a constant here?

Q: what constant?

# Motivation for static program analysis (2)

Find potential security vulnerabilities

Ex: in a server program, can a value flow from POST (untrusted, tainted source) to SQL interpreter (trusted sink) without passing through cgi.escape (a sanitizer)?

This is *taint analysis*. Can be dynamically or static.

Dynamic: mark values with a tainted bit. Sanitization clears the bit. An assertion checks that tainted values do not reach the interpreter. http://www.pythonsecurity.org/wiki/taintmode/

Static: a compile-time variant of this analysis. Proves that no input can ever make a tainted value flow to trusted sink.

# Motivation for static program analysis (3)

Optimization of virtual calls in Java:

virtual calls are costly, due to method dispatch

Idea:

Determine the target function of the call statically.

If we can prove that the call has a single target, it is safe to rewrite the virtual call so that it calls the target directly.

How to analyze whether a call has this property?

1. Based on declared (static) types of pointer variables:

   Foo a = …; a.f() // a could call Foo::f or Bar::f. Cant' tell from def of a

2. By analyzing what values flow to a=… .

   That is, we try to compute the dynamic type of a more precisely than is given by the definition "Foo a".

# Example

```
class A            { void foo() {…} }
class B extends A  { void foo() {…} }
void bar(A a) { a.foo() }  // can we optimize this call?
B myB = new B();
A myA = myB;
bar(myA);
```

Declared type of a permits a.foo() to call both A::foo and B::foo.

Yet we know only B::foo is the target, which allows optimization.

What program property would reveal that the optimization is possible?

# Client 2: Verification of casts

In Java, casts are checked at run time

- type system not expressive enough to check them statically
- although Java generics help somewhat

The anatomy of a cast check: **(Foo) e** translates to

- **if ( dynamic_type_of(e) not compatible with Foo )**
  **throw ClassCast Exception**
- t1 compatible with t2: t1 = t2 or t1 subclass of t2

Goal: prove that no exception will happen at runtime

- Why do this? The exception prevents any security holes, no?
- Such static verification useful to catch bugs (Mars Rover).

# Example

```
class SimpleContainer { Object a;
    void put (Object o) { a=o; }
    Object get() { return a; }    }
SimpleContainer c1 = new SimpleContainer();
SimpleContainer c2 = new SimpleContainer();
c1.put(new Foo()); c2.put(“Hello”);
Foo myFoo = (Foo) c1.get();  // verify that cast does not fail
```

Note: analysis must distinguish containers c1 and c2.

- otherwise c1 will appear to contain string objects

What property will lead to desired verification?

# Motivation for static program analysis (4)

Compile 164 into efficient code

If p always refers to tables that contains fields f1 and f2, we can represent the table as a struct and compile p[“f2”] into an (efficient) instruction “load from address in p + 4 bytes”.

The analysis

Determine at compile time what fields the object may ever contain at run time.

A conservative rule (conservative=sufficient but not necessary):

Compute, at compile time:

- the set of fields are added to the table using stmt e.ID=e
- the table’s fields must not be written or read through operator e[e] (only through e.ID)

# Discussion

Why is e[e] dangerous? Consider:

- p[read_input_string()]=…

creates a field whose name is unknown statically

# Example (JavaScript)

```
var p = new Foo;   // line 1
var r = p.field;
var s = {};
s[r.f] = p;
var t = s[input()];
t.g = …
```

Consider the Foo objects created in line 1:

Can we determine at compile time what fields these objects will contain during their lifetime (for any input)?

If these objects are not accessed via e[e], then we can compute (a superset of) these fields.

Can we tell if this program access Foo's via e[e]?

# Static analysis must be conservative

When **unsure**, the analysis must answer such that it does not **mislead** the client of the analysis.

- Err on the side of caution. Say, never optimize the program such that it outputs a different value.

Several ways an analysis can be **unsure:**

- Property holds on some but not all execution paths.

- Property holds on some but not all inputs.

# Misleading the client:

Constant propagation:

if x is not always a constant but is claimed to be so by the analysis to the client (the optimizer), this would lead to optimization that changes the semantics of the program. The optimizer broke the program.

Taintedness analysis:

Saying that a tainted value cannot flow may lead to missing a bug by the security engineer during program review. Yes, we want find to find all taintendness bugs, even if the analysis reports many false positives (ie many warnings are not bugs).

# What analysis that can serve these clients?

Is there a program property useful to these clients?

Yes.

We want to understand how references "flow"

References (pointer values): how are they copied from variable to variable?

Flow from **creation** of an object to its **uses**

that is, flow from new Foo to myFoo.f

Note: the pointer may flow via the heap

- that is, a pointer may be stored in an object's field
- ... and later read from this field

# Common Analysis

The flow analysis can be explained in terms of

- producers (creators of pointer values: new Foo)
- consumers (uses of the pointer value, eg, a call p.f())

Client virtual call optimization

For a given call **p.f()** we ask which expressions **new T()** produced the values that ***may*** flow to p.

we are actually interested in which values may not flow

Knowing producers will tells us possible dynamic types of p.

… and thus also the set of target methods

and thus also the set of target methods which may not be called

# Continued..

## Client cast verification

Same, but consumers are expressions **(Type) p**.

Are they also produces?

## Client 164compilation

- For each producer **new Foo** find if all consumers $e_1[e_2]$ such that the producer flows to $e_1$
- If there are no such consumers, Foo can be implemented as a struct.

# Assume Java

For now, assume we're analyzing Java

- thanks to class defs, fields of objects are known statically
- (also, assume the Java program does not use reflection)

# Flow analysis as a constant propagation

Initially we'll only handle new and assignments p=r:

```
if (…) p = new T1()
else   p = new T2()
r = p
r.f()      // what are possible dynamic types of r?
```

# Flow analysis as a constant propagation

We (conceptually) translate the program to

```
if (…) p = o1
else   p = o2
r = p
r.f()        // what are possible symbolic constant values r?
```

constants

# Abstract objects

The $o_i$ constants are called <u>abstract objects</u>

- an abstract object $o_i$ stands for any and all dynamic objects allocated at the allocation site with number i
- allocation site = a new expression
- each new expression is given a number i

When the analysis says a variable p may have value $o_7$

- we know that p may point to any object allocated in the expression "$\mathtt{new}_7$ Foo"

# We now consider pointer dereferences

```
x = new Obj();      // o1
z = new Obj();      // o2
w = x;
y = x;
y.f = z;
v = w.f;
```

To determine abstract objects that v reference, what new question do we need to answer?

Can y and w point to same object?

# Keeping track of the heap state

**Heap state:** what objects a variable may point to at a particular program point.

Heap state may change at each statement

Analyses often don't track state at each point separately

- to save space, they collapse all program points into one
- consequently, they keep a single heap state

This is called flow-insensitive analysis

why? see next slide

# Flow-Insensitive Analysis

Disregards the control flow of the program

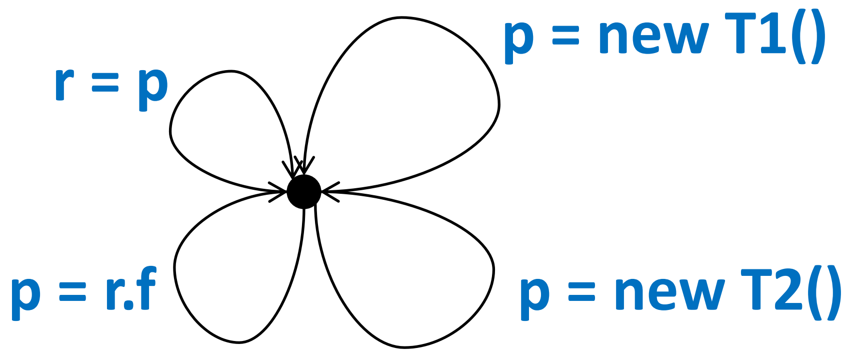
- assumes that statements can execute in any order …
- … and any number of times

Effectively, flow-insensitive analysis transforms this

**if (…) p = new T1(); else p = new T2();**

**r = p; p = r.f;**

into this control flow graph:



# Flow-Insensitive Analysis

Motivation:

- there is a single program point,
- and hence a single "version" of program state

Is flow-insensitive analysis sound?

- yes: each execution of the original program is preserved
- and thus will be analyzed and its effects reflected

But it may be imprecise

1) it adds executions not present in the original program
2) it does not distinguish value of p at distinct pgm points

# Let's develop the analysis! Canonical Stmts

Java pointers give rise to complex expressions:

- ex: **p.f().g.arr[i] = r.f.g(new Foo()).h**

Can we find a small set of canonical statements

- ie, the core language understood by the analysis
- we'll desugar the rest of the program to these stmts

We only need four canonical statements:

| | |
|---|---|
| p = new T() | *new* |
| p = r | *assign* |
| p = r.f | *getfield* |
| p.f = r | *putfield* |

# Canonical Statements, discussion

Complex statements can be canonized

```
p.f.g = r.f
    →
t1 = p.f
t2 = r.f
t1.g = t2
```

Can be done with a syntax-directed translation

like translation to byte code in PA2

# Handling of method calls

Issue 1: Arguments and return values:

- these are translated into assignments of the form p=r

Example:

```
Object foo(T x) { return x.f }
r = new T; s = foo(r.g)
```

is translated into

```
foo_retval = x.f
r = new T; s = foo_retval; x = r.g
```

# Handling of method calls

Issue 2: targets of virtual calls

- call p.f() may call many possible methods
- to do the translation shown on previous slide, must determine what these targets are

Suggest two simple methods:

- examine (static) type hierarchy (classes and subclasses)
- compute (with our flow analysis) possible dynamic types of p

# Handling of arrays

We collapse all array elements into one element

- this array element will be represented by a field arr
- ex: **p.g[i] = r** becomes **p.g.arr = r**

# Andersen’s Algorithm

For flow-insensitive flow analysis:

Goal: compute two binary relations of interest:

*x pointsTo o:* holds when x may point to abstract object o

*o flowsTo x:* holds when abstract object o may flow to x

These relations are inverses of each other

*x pointsTo o <==> o flowsTo x*

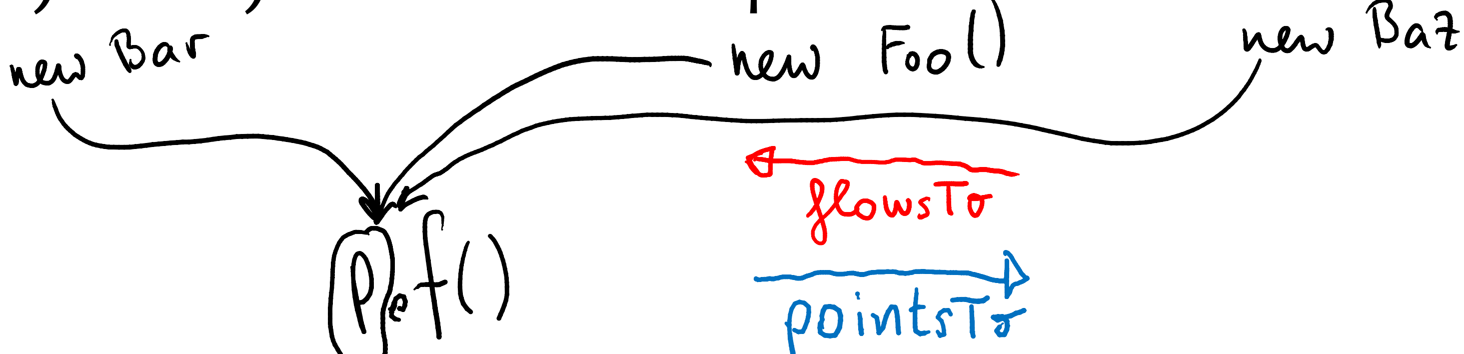
# These two relations support our clients

These relations allows determining:

1. target methods of virtual calls
2. verification of casts
3. how JavaScript objects are used

For 3) we need the flowsTo relation

For 1) and 2) we need the x pointsTo o relation



# Inference rule (1)

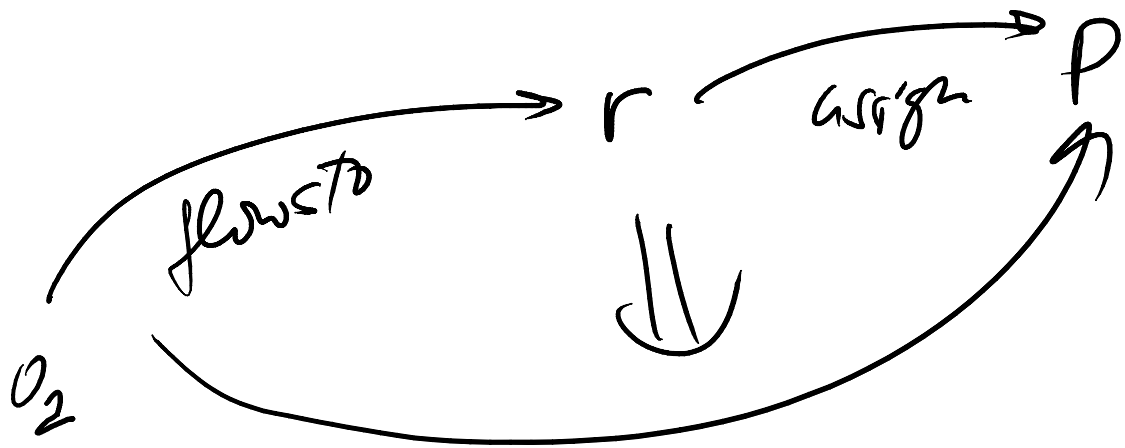
p = $\text{new}_i$ T() $\quad\quad$ $o_i$ *new p*

$o_i$ new $p \rightarrow o_i$ *flowsTo* $p$

# Inference rule (2)

p = r *r assign p*

$o_i$ *flowsTo r* $\wedge$ *r assign p* $\rightarrow$ $o_i$ *flowsTo p*



# Inference rule (3)

p.f = a $\quad\quad$ $a \;\; pf(f) \;\; p$

b = r.f $\quad\quad$ $r \;\; gf(f) \;\; b$

$$o_i \; flowsTo \; a \quad \wedge \quad a \; pf(f) \; p \quad \wedge \quad p \; alias \; r \quad \wedge \quad r \; gf(f) \; b$$
$$\rightarrow \; o_i \; flowsTo \; b$$

# Inference rule (4)

it remains to define *x alias y*

(x and y may point to same object):

$$o_i \text{ flowsTo } x \wedge o_i \text{ flowsTo } y \rightarrow x \text{ alias } y$$

# Prolog program for Andersen algorithm

```
new(o1,x).        % x=new_1 Foo()
new(o2,z).        % z=new_2 Bar()
assign(x,y).      % y=x
assign(x,w).      % w=x
pf(z,y,f).        % y.f=z
gf(w,v,f).        % v=w.f

flowsTo(O,X) :- new(O,X).
flowsTo(O,X) :- assign(Y,X), flowsTo(O,Y).
flowsTo(O,X) :- pf(Y,P,F), gf(R,X,F), aliasP,R), flowsTo(O,Y).

alias(X,Y)   :- flowsTo(O,X), flowsTo(O,Y).
```

# How to use the result of the analysis?

When the analysis infers *o* flowsTo *y*, *w*hat did we prove?

- nothing useful, usually, since *o* flowsTo *y* does not imply that there is a program input for which o will definitely flow to y.

The useful result is when the analysis ***can't*** infer *o* flowsTo *y*

- then we have proved that o **cannot** flow to y for any input
- this is useful information!
- it may lead to better optimization, verification, compilation

Same arguments apply to alias, pointsTo relations

- and other static analyses in general

# Inference Example (1)

The program:

```
x = new Foo(); // o1
z = new Bar(); // o2
w = x;
y = x;
y.f = z;
v = w.f;
```

# Inference Example (2):

The program is converted to six facts:

$o_1$ new $x$

$x$ assign w

$z$ pf($f$) y

$o_2$ new $z$

$x$ assign $y$

$w$ gf($f$) $v$

# Inference Example (3), infering facts

$o_1$ new $x$ — $o_2$ new $z$

$x$ assign $w$ — $x$ assign $y$

$z$ pf($f$) $y$ — $w$ gf($f$) $v$

The inference:

$o_1$ new $x$ $\longrightarrow$ $o_1$ flowsTo $x$

$o_2$ new $z$ $\longrightarrow$ $o_2$ flowsTo $z$

$o_1$ flowsTo $x$ $\wedge$ $x$ assign $w$ $\longrightarrow$ $o_1$ flowsTo $w$

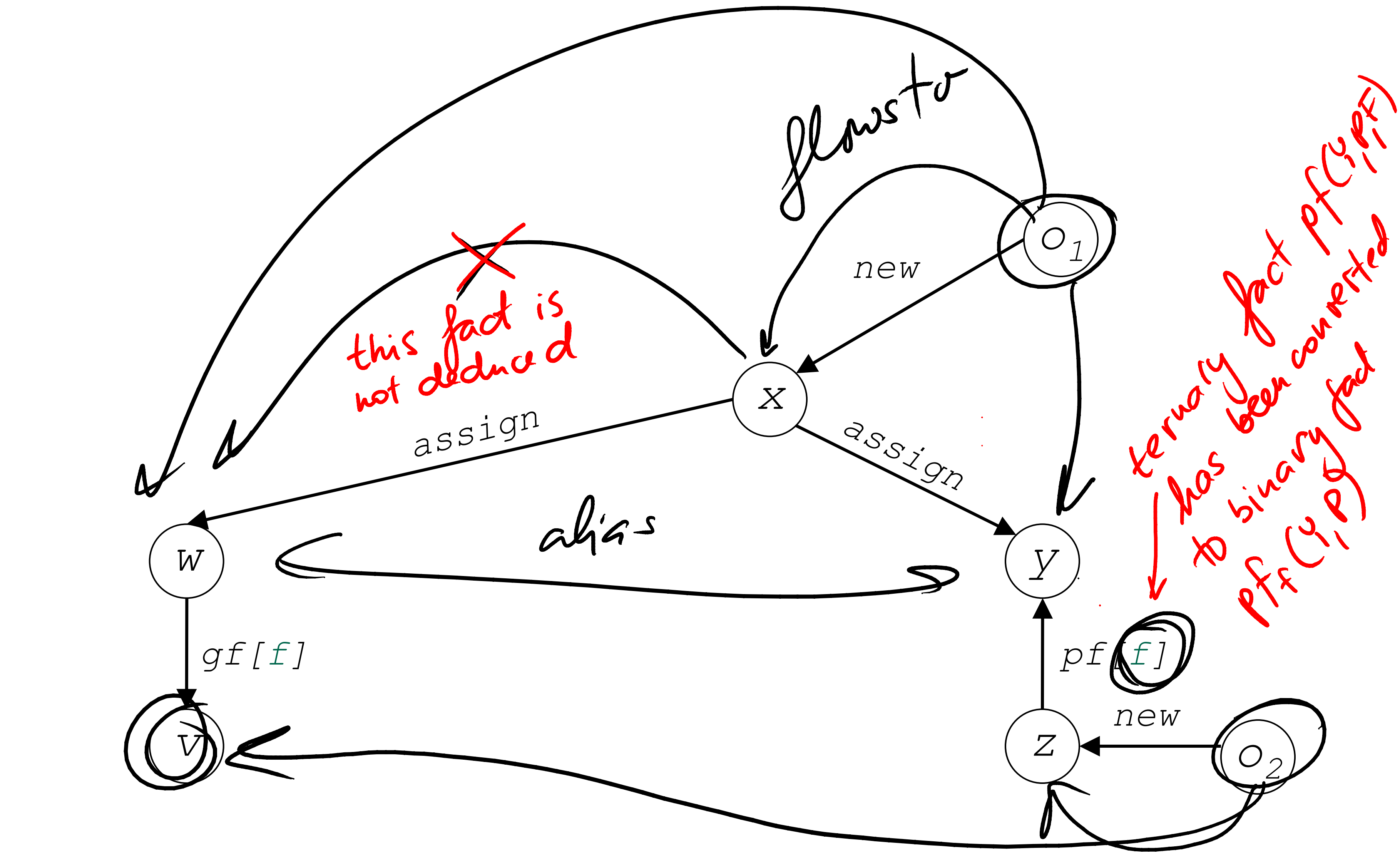
$o_1$ flowsTo $x$ $\wedge$ $x$ assign $y$ $\longrightarrow$ $o_1$ flowsTo $y$

$o_1$ flowsTo $y$ $\wedge$ $o_1$ flowsTo $w$ $\longrightarrow$ $y$ alias $w$

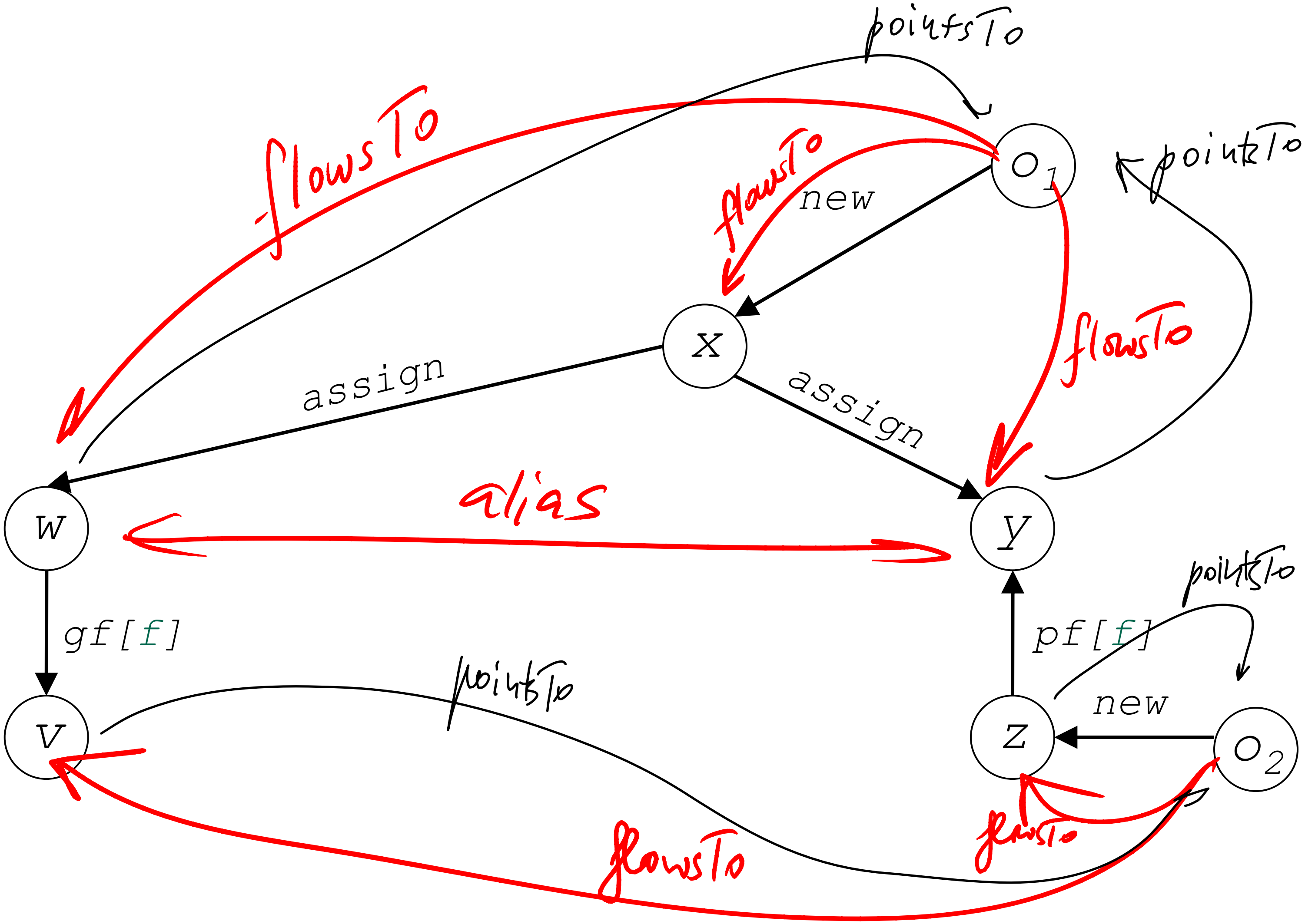
$o_2$ flowsTo $z$ $\wedge$ $z$ pf($f$) $y$ $\wedge$ $y$ alias $w$ $\wedge$ $w$ gf($f$) $v$ $\longrightarrow$
$o_2$ flowsTo $v$

…

# Example: visualizing Prolog deductions



# Example, deriving the relations



# Example (4):

Notes:

- inference must continue until no new facts can be derived
- only then we know we have performed sound analysis

Conclusions from our example inference:

- we have inferred $o_2$ flowsTo *v*
- we have NOT inferred $o_1$ flowsTo *v*
- hence we know v will point only to instances of Bar
- (assuming the example contains the whole program)
- thus casts (Bar) v will succeed
- similarly, calls v.f() are optimizable

# “Parsing the graph”

Visualization of inferences on slides 41 and 42 parses the strings in the “graph of binary facts” using the CYK algorithm (Lecture 8)

Details on this style of inference are in the rest of the slide, under CFL-reachability (optional material)

# Adaptation for JavaScript

Need to handle more language constructs:

- property read $e_1[e_2]$
- property write $e_1[e_2] = e_3$

Extensions to the algorithm:

- analysis must determine whether an object might appear as $e_1$ in $e_1[e_2] = e_3$
- if yes, we must conservatively assume that we don't know objects fields
- more similar rules are needed …

# Summary

Determine run-time properties of programs statically

– example property: “is variable x a constant?”

Statically: without running the program

– it means that we don’t know the inputs
– and thus must consider all possible program executions

We want *sound* analysis: err on the side of caution.

– allowed to say x is not a constant when it is
– not allowed to say x is a constant when it is not

Static analysis has many clients

– optimization, verification, compilation

# The technique

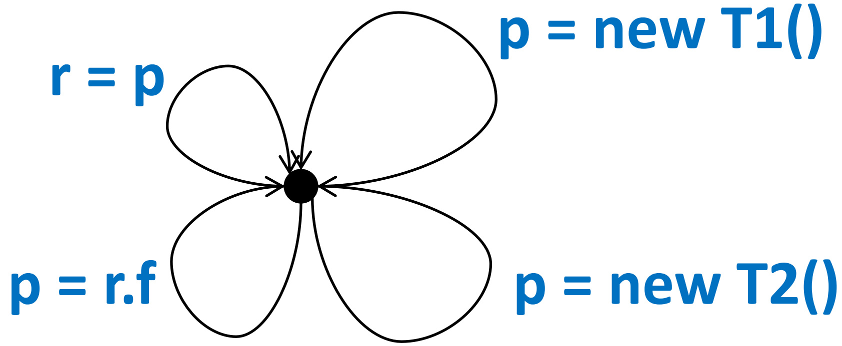
Flow-insensitive analysis:

- collapse into one all program points (ie, stmt entry and exits)
- reduces the amount of analysis state to maintain
- reduces precision, too, of course

Transform this program

```
if (...) p = new T1();
else p = new T2();
r = p; p = r.f;
```

into this one:



# Andersen's algorithm

- Deduces the flowsTo relation from program statements
  - statements are facts
  - analysis is a set of inference rules
  - flowsTo relation is a set of facts inferred with analysis rules
- Statement facts: we'll write them as *x predicateName y*
  - $p = new_i\ T()$ $\quad$ $o_i$ *new p*
  - p = r $\quad$ *r assign p*
  - p = r.f $\quad$ *r gf(f) p*
  - p.f = r $\quad$ *r pf(f) p*

# CFL-Reachability

deduction via parsing of a graph

# Inference via graph reachability

Prolog's search is too general and expensive.

may in general backtrack (exponential time)

Can we replace it with a simpler inference algorithm?

possible when our inference rules have special form

We will do this with CFL-rechability

it's a generalized graph reachability

# (Plain) graph reachability

Reachability Def.:

Node x is **reachable** from a node y in a directed graph G if there is a path p from y to x.

How to compute reachability?

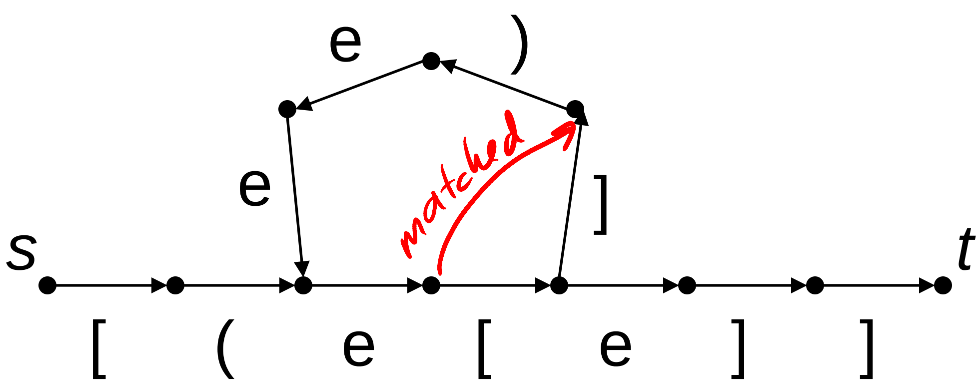
depth-first search, complexity O(N+E)

# Context-Free-Language-Reachability

CFL-Reachability Def.:

Node x is ***L*-reachable** from a node y in a directed labeled graph G if

- there is a path p from y to x, and
- path p is labeled with a string from a context free language L.




**The context-free language L:**

*matched* → *matched matched*
| ( *matched* )
| [ *matched* ]
| *e*
| $\varepsilon$

Is t reachable from s according to the language L?

# Computing CFL-reachability

Given

- a labeled directed graph P and
- a grammar G with a start nonterminal S,

we want to compute whether x is S-reachable from y

- for all pairs of nodes x,y
- or for a particular x and all y
- or for a given pair of nodes x,y

We can compute CFL-reachability with CYK parser

- x is S-reachable from y if CYK adds an S-labeled edge from y to x
- $O(N^3)$ time

# Convert inference rules to a grammar

The inference rules

ancestor(P,C) :- parentof(P,C).

ancestor(A,C) :- ancestor(A,P), parentof(P,C).

Language over the alphabet of edge labels

ANCESTOR ::= parentof

| ANCESTOR parentof

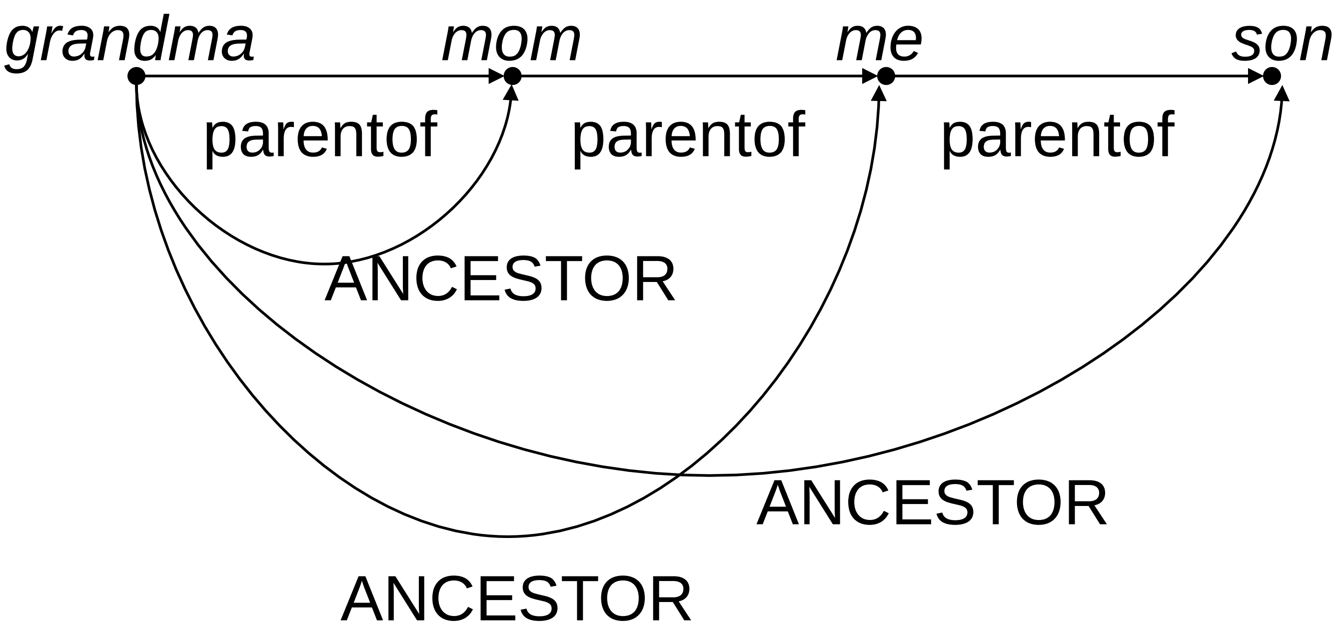
Notes:

- initial facts are terminals (perentof)
- derived facts are non-terminals (ANCESTOR)

## So, which rules can be converted to CFL-reachability?

ANCESTOR ::= parentof | ANCESTOR parentof

Is "son" ANCESTOR-reachable from "grandma"?



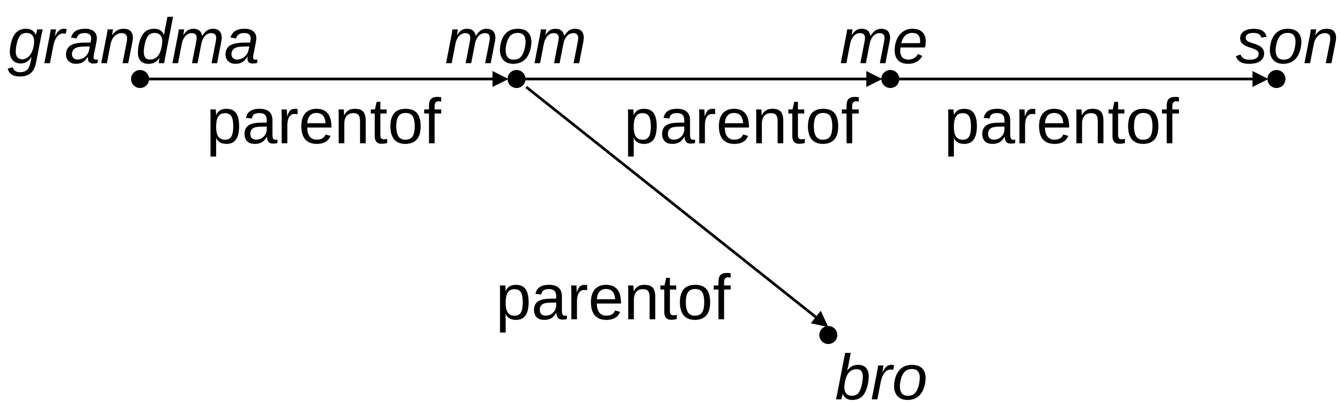
# What rules can we convert to CFL-rechability?

Let's add a rule for SIBLING:

ANCESTOR ::= parentof | ANCESTOR parentof

SIBLING ::= ???

We want to ask whether "bro" is SIBLING-reachable from "me".



# Conditions for conversion to CFL-rechability

- Not all inference rules can be converted
- Rules must form a “chain program”
- Each rule must be of the form:

  foo(A,D) :- bar(A,B), baz(B,C), baf(C,D)

- Ancestor rules have this form

  ancestor(A,C) :- ancestor(A,P), parentof(P,C).

- But the Sibling rules cannot be written in chain form
  - why not?  think about it also from the CFL-reachability angle
  - no path from x to its sibling exists, so no SIBLING-path exists
    - no matter how you define the SIBLING grammar

# Andersen's Algorithm with Chain Program

converts the analysis into a graph parsing problem

# Back to Andersen's analysis

Rules in logic programming form:

```
flowsTo(O,X) :- new(O,X).
flowsTo(O,X) :- flowsTo(O,Y), assign(Y,X).
flowsTo(O,X) :- flowsTo(O,Y), pf(Y,P,F), alias(P,R),
   gf(R,X,F).
alias(X,Y)   :- flowsTo(O,X), flowsTo(O,Y).
```

Problem: some predicates are not binary

# Andersen's algorithm inference rules

Translate to binary form

put field name into predicate name,

must replicate the third rule for each field in the program

```
flowsTo(O,X) :- new(O,X).
flowsTo(O,X) :- flowsTo(O,Y), assign(Y,X).
flowsTo(O,X) :- flowsTo(O,Y), pf[F](Y,P),
                alias(P,R), gf[F](R,X).
alias(X,Y)   :- flowsTo(O,X), flowsTo(O,Y).
```

# Andersen's algorithm inference rules

Now, which of these rules have the chain form?

| | |
|---|---|
| flowsTo(O,X) :- new(O,X). | yes |
| flowsTo(O,X) :- flowsTo(O,Y), assign(Y,X). | yes |
| flowsTo(O,X) :- flowsTo(O,Y), pf[F](Y,P), alias(P,R), gf[F](R,X). | yes |
| alias(X,Y) :- flowsTo(O,X), flowsTo(O,Y). | no |

# Making alias a chain rule

We can easily make alias a chain rule with pointsTo. Recall:

flowsTo(O,X) :- pointsTo(X,O)

pointsTo(X,O) :- flowsTo(O,X)

Hence

alias(X,Y) :- pointsTo(X,O), flowsTo(O,Y).

If we could derive **chain** rules for pointsTo, we would be done. Let's do that.

# Idea: add terminal edges also in opposite direction

For each edge o new x, add edge x $new^{-1}$ o

- same for other terminal edges

Rules for pointsTo will refer to the inverted edges

- but otherwise these rules are analogous to flowsTo

What it means for CFL reachability?

there exists a path from o to x labeled with $s \in L(flowsTo)$

$\Leftrightarrow$

there exists a path from x to o labeled with $s' \in L(pointsTo)$.

# Inference rules for pointsTo

$p = new_i\ T()$ $o_i$ new $p$ $p$ $new^{-1}$ $o_i$

$o_i$ new $p$ → $o_i$ flowsTo $p$ Rule 1
$p$ $new^{-1}$ $o_i$ → $p$ pointsTo $o_i$ Rule 5

$p = r$ $r$ assign $p$ $p$ $assign^{-1}$ $r$

$o_i$ flowsTo $r$ and $r$ assign $p$ → $o_i$ flowsTo $p$ Rule 2
$p$ $assign^{-1}$ $r$ and $r$ pointsTo $o_i$ → $p$ pointsTo $o_i$ Rule 6

# Inference rules for pointsTo (Part 2)

We can now write *alias* as a chain rule.

p.f = a  
b = r.f

a pf(f) p  
r gf(f) b

p $pf(f)^{-1}$ a  
b $gf(f)^{-1}$ r

$o_i$ flowsTo a $\wedge$ a pf(f) p $\wedge$ p alias r $\wedge$ r gf(f) b $\rightarrow$ $o_i$ flowsTo b  
b $gf(f)^{-1}$ r $\wedge$ r alias p $\wedge$ p $pf(f)^{-1}$ a $\wedge$ a flowsTo $o_i$ $\rightarrow$ b pointsTo $o_i$  
Rules 3, 7

Both flowsTo and pointsTo use the same alias rule:  
x pointsTo $o_i$ $\wedge$ $o_i$ flowsTo y $\rightarrow$ x alias y Rule 8

# The reachability language

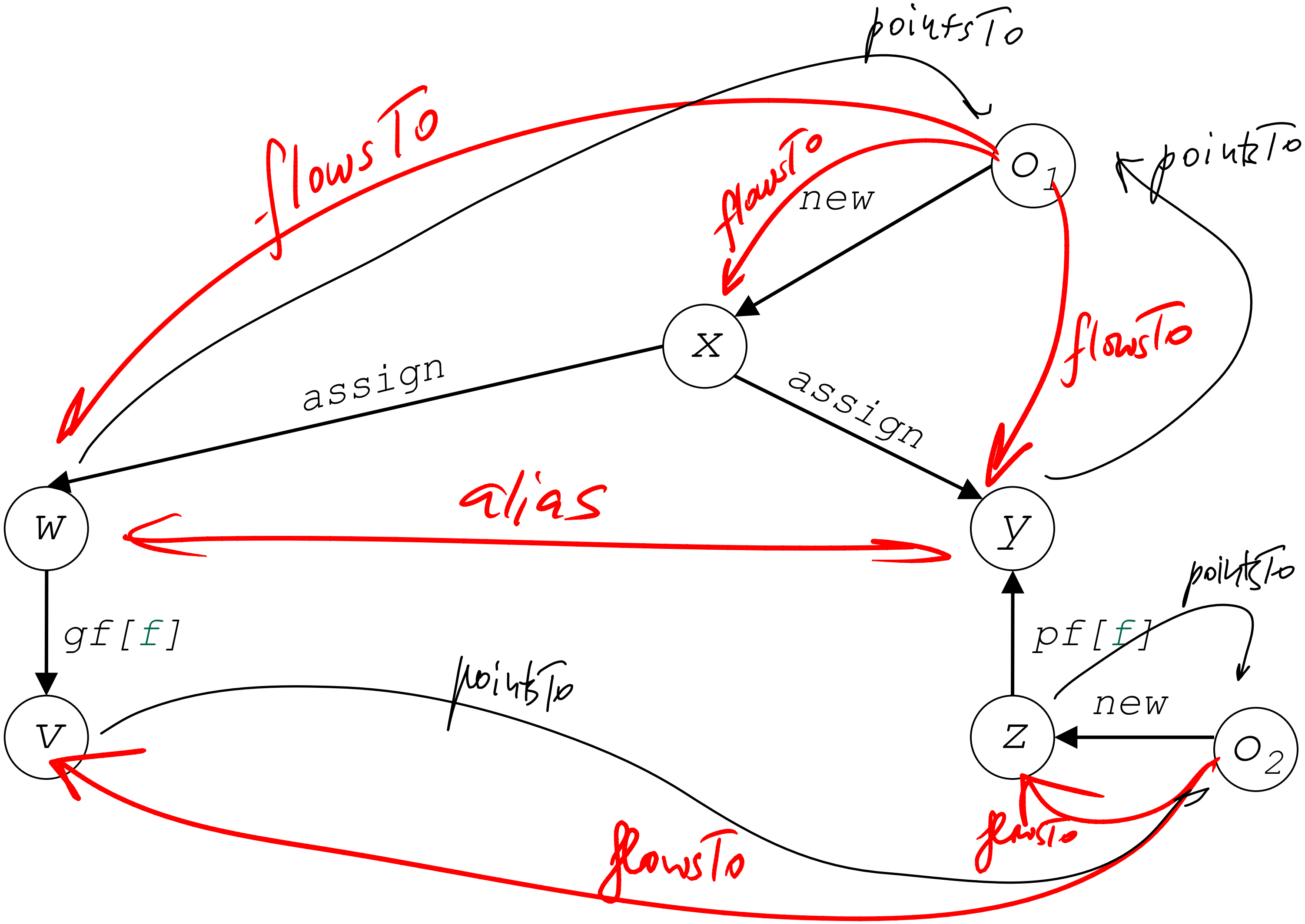
All rules are chain rules now

- directly yield a CFG for flowsTo, pointsTo via CFL-reachability :

$$
\begin{aligned}
\text{flowsTo} &\rightarrow \text{new} \\
\text{flowsTo} &\rightarrow \text{flowsTo assign} \\
\text{flowsTo} &\rightarrow \text{flowsTo pf[f] alias gf[f]} \\
\text{pointsTo} &\rightarrow \text{new}^{-1} \\
\text{pointsTo} &\rightarrow \text{assign}^{-1} \text{ pointsTo} \\
\text{pointsTo} &\rightarrow \text{gf[f]}^{-1} \text{ alias pf[f]}^{-1} \text{ pointsTo} \\
\text{alias} &\rightarrow \text{pointsTo flowsTo}
\end{aligned}
$$

# Example: computing pointsTo-, flowsTo-reachability

Inverse terminal edges not shown, for clarity.



# Summary (Andersen via CFL-Reachability)

The pointsTo relation can be computed efficiently

- with an $O(N^3)$ graph algorithm

Surprising problems can be reduced to parsing

- parsing of graphs, that is

# CFL-Reachability: Notes

The context-free language acts as a filter

- filters out paths that don't follow the language

We used the filter to model program semantics

- we filter out those pointer flows that cannot actually happen

What do we mean by that?

- consider computing *x pointsTo o* with "plain" reachability
  - plain = ignore edge labels, just check if a path from x to o exists
- is this analysis sound? yes, we won't miss anything
  - we compute a *superset* of pointsTo relation based on CFL-reachability
- but we added infeasible flows, example:
  - wrt plain reachability, pointer stored in p.f can be read from p.g