Pointer Analysis

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Goals

- *Points-to Analysis*: Determine the set of possible values of a pointer-variable (at different points in a program)
  - what locations can a pointer point-to?
- *Alias Analysis*: Determine if two pointer-variables may point to the same location
- Compute conservative approximation
- A fundamental analysis, required by most other static analyses

A Constant Propagation Example

```
x = 3;

y = 4;

z = x + 5;
```

- x is always 3 here
- can replace x by 3
- and replace x+5 by 8
- and so on

A Constant Propagation Example With Pointers

```
x = 3;

*p = 4;

z = x + 5;
```

- Is x always 3 here?

A Constant Propagation Example With Pointers

```
p = &y;
x = 3;
*p = 4;
z = x + 5;
```

```
if (?)
  p = &x;
else
  p = &y;
x = 3;
```

```
p = &x;
x = 3;
*p = 4;
z = x + 5;
```

x is alway

always 4

pointers affect
most program analyses

x may be 3 or 4
(i.e., x is unknown in our lattice)

A Constant Propagation Example With Pointers

```
p = &y;
x = 3;
*p = 4;
z = x + 5;
```

p always points-to y

```
if (?)
  p = &x;
else
  p = &y;
x = 3;
*p = 4;
z = x + 5;
```

p may point-to x or y

```
p = &x;
x = 3;
*p = 4;
z = x + 5;
```

p always points-to x

Points-to Analysis

- Determine the set of targets a pointer variable could point-to (at different points in the program)
  - "p points-to x"
    - "p stores the value &x"
    - "*p denotes the location x"
  - targets could be variables or locations in the heap (dynamic memory allocation)
    - p = &x;
    - p = new Foo(); or p = malloc (…);

Algorithm A (may points-to analysis)
A Simple Example

```
p = &x;
q = &y;
if (?) {
   q = p;
}
x = &a;
y = &b;
z = *q;
```

Algorithm A (may points-to analysis)
A Simple Example

```
p = &x;
q = &y;
if (?) {
   q = p;
}
x = &a;
y = &b;
z = *q;
```

p	q	x	y	z

Algorithm A (may points-to analysis) A Simple Example

```
x = &a;
y = &b;
if (?) {
  p = &x;
} else {
  p = &y;
}

*x = &c;
*p = &c;
```

How should we handle this statement? (Try it!)

Weak update

Strong update

x: a	: b	p: {x,y}	null
x: a	: b	p: {x,y}	a: c
x: {a,c}	y: {b,c}	p: {x,y}	a: c

Questions

- When is it correct to use a strong update? A weak update?
- Is this points-to analysis precise?
- We must formally define what we want to compute before we can answer many such questions

Points-To Analysis: An Informal Definition

- Let u denote a program-point
- Define IdealMayPT (u) to be

$$\{ (p,x) \mid p \text{ points-to } x \text{ in some state at } u \text{ in some run } \}$$

- Algorithm should compute a set MayPT(u) that over-approximates above set

Static Program Analysis

- A static program analysis computes approximate information about the runtime behavior of a given program
  1. The set of valid programs is defined by the programming language syntax
  2. The runtime behavior of a given program is defined by the programming language semantics
  3. The analysis problem defines what information is desired
  4. The analysis algorithm determines what approximation to make

Programming Language: Syntax

- A program consists of
  - a set of variables Var
  - a directed graph (V,E,entry) with a distinguished entry vertex, with every edge labelled by a primitive statement
- A primitive statement is of the form
  - x = null
  - x = y
  - x = *y
  - x = &y;
  - *x = y
  - skip

  (where x and y are variables in Var)

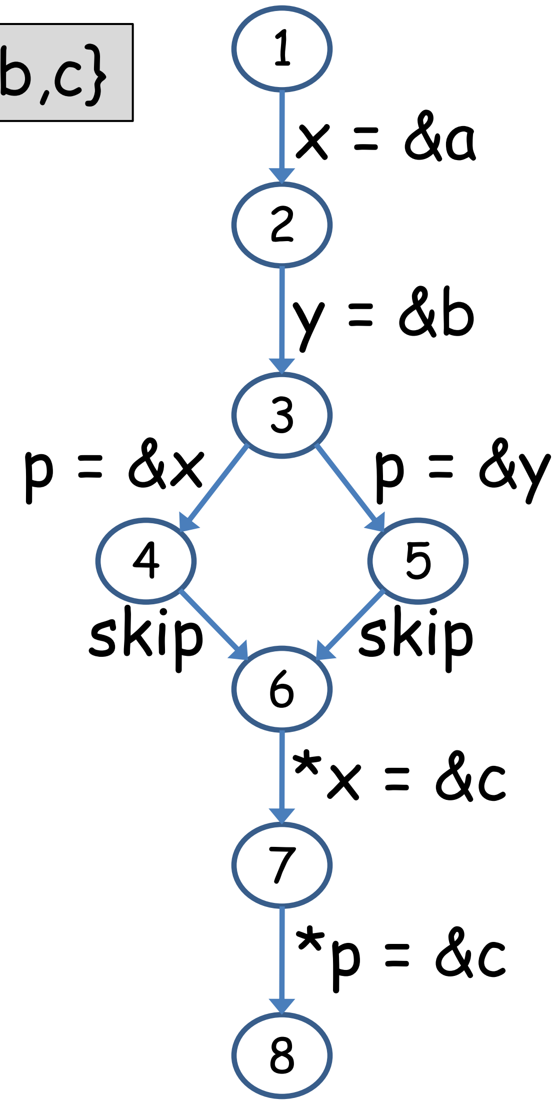
Omitted (for now)
- Dynamic memory allocation
- Pointer arithmetic
- Structures and fields
- Procedures

Example Program

```
x = &a;
y = &b;
if (?) {
   p = &x;
} else {
   p = &y;
}

*x = &c;
*p = &c;
```

Vars = {x,y,p,a,b,c}

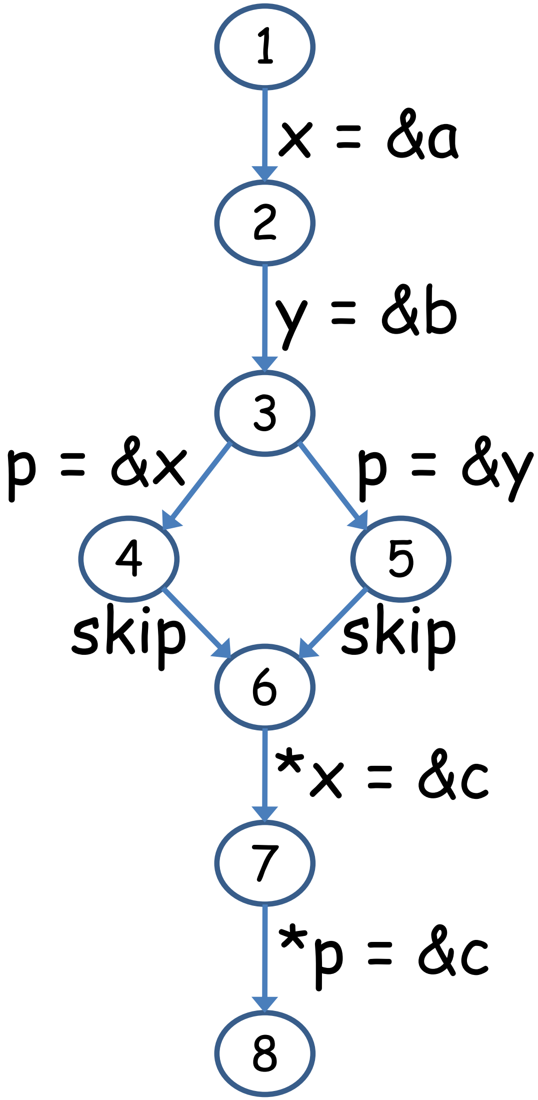


Programming Language: Operational Semantics

- Operational semantics == an interpreter (defined mathematically)
- State
  - DataState ::= Var -> (Var U {null})
  - PC ::= V (the vertex set of the CFG)
  - ProgramState ::= PC x DataState
- Initial-state:
  - (entry, \x. null)

Example States

Vars = {x,y,p,a,b,c}



Initial data-state

x: N, y:N, p:N, a:N, b:N, c:N

Initial program-state

<1, x: N, y:N, p:N, a:N, b:N, c:N >

Next program-state

<2, x: a, y:N, p:N, a:N, b:N, c:N >

Programming Language: Operational Semantics

- Meaning of primitive statements
  - CS[stmt] : DataState -> $2^{\text{DataState}}$

- CS[x = null] s = $\{s[x \to null]\}$
- CS[x = &y] s = $\{s[x \to y]\}$
- CS[x = y] s = $\{s[x \to s(y)]\}$
- CS[x = *y] s = …

…

…

- CS[*x = y] s = …

…

= …

Programming Language: Operational Semantics

- Meaning of primitive statements
  - CS[stmt] : DataState -> $2^{DataState}$

- CS[x = null] s = {s[x → null]}
- CS[x = &y] s = {s[x → y]}
- CS[x = y] s = {s[x → s(y)]}
- CS[x = *y] s = {s[x → s(s(y))]},

  if s(y) is not null

  = {}, otherwise
- CS[*x = y] s = …

  …

  …

Programming Language: Operational Semantics

- Meaning of primitive statements
  - $CS[stmt] : DataState \rightarrow 2^{DataState}$

- $CS[\ x = null\ ]\ s = \{s[x \rightarrow null]\}$
- $CS[\ x = \&y\ ]\ s = \{s[x \rightarrow y]\}$
- $CS[\ x = y\ ]\ s = \{s[x \rightarrow s(y)]\}$
- $CS[\ x = {*}y\ ]\ s = \{s[x \rightarrow s(s(y))]\}$, if $s(y)$ is not null
  $= \{\}$, otherwise
- $CS[{*}x = y\ ]\ s = \{s[s(x) \rightarrow s(y)]\}$, if $s(x)$ is not null
  $= \{\}$, otherwise

Programming Language: Operational Semantics

- Meaning of program
  - a transition relation $\rightarrow$ on program-states
  - $\rightarrow \subseteq$ ProgramState X ProgramState
  - $state_1 \rightarrow state_2$ means that the execution of some edge in the program can transform $state_1$ into $state_2$
- Defining $\rightarrow$
  - $(u,s) \rightarrow (v,s')$ iff the program contains a control-flow edge u->v labelled with a statement stmt such that CS[stmt]s = s'

Programming Language: Operational Semantics

- A sequence of states $s_1 s_2 \ldots s_n$ is said to be an execution (of the program) iff
  - s_1 is the Initial-State
  - $s_i \rightarrow s_{i+1}$ for 1 <= I < n
- A state s is said to be a reachable state iff there exists some execution $s_1 s_2 \ldots s_n$ is such that $s_n = s$.
- Define RS(u) = { s | (u,s) is reachable }

Programming Language: Operational Semantics

- A sequence of states $s_1 s$... is said to be an execution (of the
  - s_1 is the Initial-State
  - $s_i \rightarrow s_{i+1}$ for $1 <= I < n$
- A state s is said to be a reachable state iff there exists some execution $s_1 s_2 \ldots s_n$ is such that $s_n = s$.
- Define $RS(u) = \{ s \mid (u,s) \text{ is reachable} \}$

This is the collecting semantics at point *u*

Ideal Points-To Analysis: Formal Definition

- Let u denote a vertex in the CFG

- Define IdealMayPT (u) to be
  \p. { x | exists s in RS(u). s(p) == x }

May-Point-To Analysis: Problem statement

Compute MayPT: V -> $2^{Var'}$ such that for every vertex u
MayPT(u) $\supseteq$ IdealMayPT(u)
(where Var' = Var U {null})

May-Point-To Algorithms

Compute MayPT: $V \to 2^{Vars'}$ such that
$MayPT(u) \supseteq IdealMayPT(u)$

- An algorithm is said to be correct if the solution MayPT it computes satisfies
  $$\forall u \in V.\ MayPT(u) \supseteq IdealMayPT(u)$$
- An algorithm is said to be precise if the solution MayPT it computes satisfies
  $$\forall u \in V.\ MayPT(u) = IdealMayPT(u)$$
- An algorithm that computes a solution MayPT1 is said to be more precise than one that computes a solution MayPT2 if
  $$\forall u \in V.\ MayPT1(u) \subseteq MayPT2(u)$$

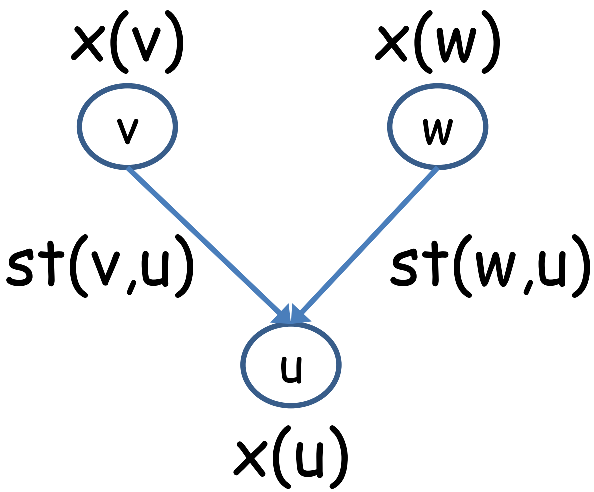
Algorithm A: A Formal Definition
The "Data Flow Analysis" Recipe

- Define semi-lattice of abstract-values
  - AbsDataState ::=

    $(Var \rightarrow (2^{Var'} - \{\})) \cup \{bot\}$
  - $f_1 \cup f_2 = \backslash x. (f_1 (x) \cup f_2 (x))$
- Define initial abstract-value
  - InitialAbsState = \x. {null}
- Define transformers for primitive statements
  - AS[stmt] : AbsDataState -> AbsDataState

Algorithm A: A Formal Definition
The "Data Flow Analysis" Recipe

- Let st(v,u) denote stmt on edge v->u



- Compute the least-fixed-point of the following "dataflow equations"
  – $x(entry) = InitialAbsState$
  – $x(u) = \cup_{v\text{->}u} AS(st(v,u))\ x(v)$

Algorithm A: The Transformers

- Abstract transformers for primitive statements
  - AS[stmt] : AbsDataState -> AbsDataState
- AS[x = y] s = $s[x \rightarrow s(y)]$
- AS[x = null] s = $s[x \rightarrow \{null\}]$
- AS[x = &y] s = $s[x \rightarrow \{y\}]$
- AS[x = *y] s = $s[x \rightarrow s^*(s(y) - \{null\})]$, if s(y) is not = {null}
  = bot, otherwise

where $s^*(\{v_1, \ldots, v_n\}) = s(v_1) \cup \ldots \cup s(v_n)$,

Algorithm A

- AS[$*x = y$] s =

$$
\begin{cases}
bot & \text{if } s(x) = \{null\} \\
s[z \to s(y)] & \text{if } s(x) - \{null\} = \{z\} \\
s[z_1 \to s(z_1) \cup s(y)] & \text{if } s(x) - \{null\} = \{z_{1, \ldots,} z_k\} \\
\quad [z_2 \to s(z_2) \cup s(y)] & (\text{where } k > 1) \\
\quad \ldots & \\
\quad [z_k \to s(z_k) \cup s(y)] &
\end{cases}
$$

- After fix-point solution is obtained, AbsDataState(u) is emitted as MayPT(u), for each program point u

An alternative algorithm: must points-to analysis

- AbsDataState is modified, as follows:
  - Each var is mapped to {} or to a singleton set
  - join is point-wise intersection

- Let MustPT(u) be fix-point at u

- Guarantee: Υ(MustPT(u)) $\supseteq$ MayPT(u) $\supseteq$ IdealMayPT(u)

where Υ(S) = S,
if S is a singleton set
= Var', if S = {}

Must points-to analysis algorithm

- AS transfer functions same as in Algorithm A for $x = y$, $x = null$, and $x = \&y$
- AS[$x = *y$] s

$$
\begin{aligned}
&= bot, && \text{if } s(y) = \{null\} \\
&= s[x \rightarrow \{\}], && \text{if } s(y) = \{\} \\
&= s[x \rightarrow s(z)], && \text{if } s(y) = \{z\}
\end{aligned}
$$

Must points-to analysis algorithm

- AS[*x = y] s = bot,
  if s(x) = {null}
  = s[z → s(y)]
  if s(x) = {z}
  = \v. {},
  otherwise

This analysis is less precise than the may-points-to analysis (Algorithm A), but is more efficient