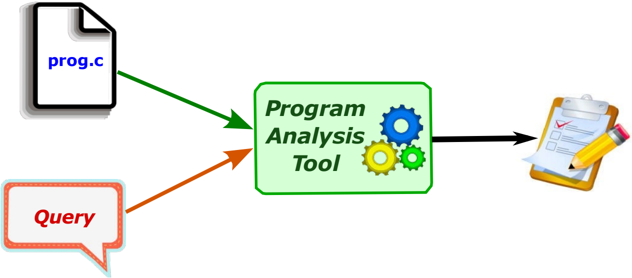
Advanced Programming Methods
Seminar

Introduction in program analysis

Introduction in program analysis

What is Program Analysis?

- Very broad topic, but generally speaking, automated analysis of program behavior
- Program analysis is about developing algorithms and tools that can analyze other programs



Applications of Program Analysis

- Bug finding. e.g., expose as many assertion failures as possible
- Security. e.g., does an app leak private user data?
- Verification. e.g., does the program always behave according to its specification?
- Compiler optimizations. e.g., which variables should be kept in registers for fastest memory access?
- Automatic parallelization. e.g., is it safe to execute different loop iterations on parallel?

Dynamic vs. Static Program Analysis

- Two flavors of program analysis:
  - Dynamic analysis: Analyzes program while it is running
  - Static analysis: Analyzes source code of the program

Static

\+ reasons about all executions

\- less precise

Dynamic

\+ more precise

\- results limited to observed executions

Testing /Formal Verification

A very crude dichotomy:

Testing	Formal Verification
Correct with respect to the *set of test inputs*, and reference system	Correct with respect to *all inputs*, with respect to a *formal specification*
Easy to perform	Decidability problems, Computational problems,
Dynamic	Static

Static Program Analysis

- Typical static analysis question: "Given source code of program P and desired property Q, does P exhibit Q in all possible executions?"

But this question is undecidable! This means

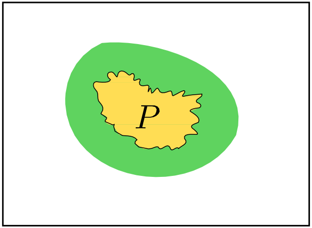
static analyses are either:

- Unsound: May say program is safe even though it is unsafe
- Sound, but incomplete: May say program is unsafe even though it is safe
- Non-terminating: Always gives correct answer when it terminates, but may run forever

Many static analysis techniques are sound but incomplete.

How to design Sound Static Analyses

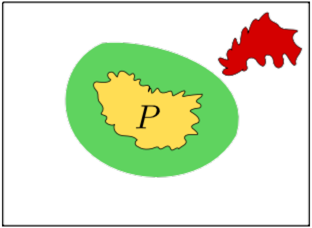
Key idea: Overapproximate (i.e., abstract) program behavior



How to design Sound Static Analyses

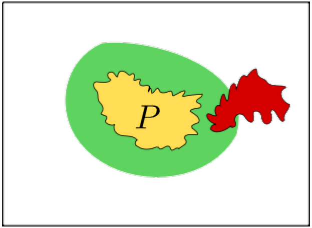
Key idea: Overapproximate (i.e., abstract) program behavior

- Bad states outside over-approximation
  $\Rightarrow$ Program safe



How to design Sound Static Analyses

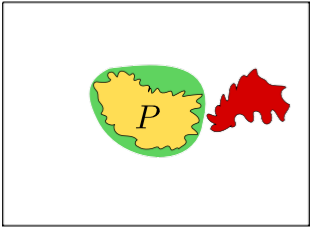
Key idea: Overapproximate (i.e., abstract) program behavior



- Bad states outside over-approximation
  ⇒ Program safe
- Bad states inside over-approximation, but outside P
  ⇒ false alarm

How to design Sound Static Analyses

Key idea: Overapproximate (i.e., abstract) program behavior



- Bad states outside over-approximation
  ⇒ Program safe
- Bad states inside over-approximation, but outside *P*
  ⇒ false alarm

⇒ Goal: Construct abstractions that are precise enough (i.e., few false alarms) and that scale to real programs

Examples of Abstractions

There is no "one size fits all" abstraction

- What information is useful depends on what you want to prove about the program!

Examples of Abstractions

There is no "one size fits all" abstraction

- What information is useful depends on what you want to prove about the program!

Application	Useful abstraction
No division-by-zero errors	zero vs. non-zero
Data structure verification	list, tree, graph, . . .
No out-of-bounds array accesses	ranges of integer variables

How to create Sound Abstractions

- Useful theory for understanding how to design sound static analyses is abstract interpretation
  - Seminal '77 paper by Patrick & Radhia Cousot
- Not a specific analysis, but rather a framework for designing sound-by-construction static analyses
- Let's look at an example: A static analysis that tracks the sign of each integer variable (e.g., positive, non-negative, zero etc.)

First Step: Design An Abstract Domain

- An abstract domain is just a set of abstract values we want to track in our analysis

- For our example, let's fix the following abstract domain:
  - pos: $\{x \mid x \in \mathbb{Z} \wedge x > 0\}$
  - zero: $\{0\}$
  - neg: $\{x \mid x \in \mathbb{Z} \wedge x < 0\}$
  - non-neg: $\{x \mid x \in \mathbb{Z} \wedge x \geq 0\}$

First Step: Design An Abstract Domain

- An abstract domain is just a set of abstract values we want to track in our analysis

- For our example, let's fix the following abstract domain:
  - pos: $\{x \mid x \in \mathbb{Z} \wedge x > 0\}$
  - zero: $\{0\}$
  - neg: $\{x \mid x \in \mathbb{Z} \wedge x < 0\}$
  - non-neg: $\{x \mid x \in \mathbb{Z} \wedge x \geq 0\}$

- In addition, every abstract domain contains:
  - $\top$ (top): "Don't know", represents any value
  - $\perp$ (bottom): Represents empty-set

- Abstraction function (α) maps sets of concrete elements to the most precise value in the abstract domain

Second Step: Abstraction and Concretization Function

- Abstraction function (α) maps sets of concrete elements to the most precise value in the abstract domain
  - $\alpha(\{2, 10, 0\}) =$ non-neg
  - $\alpha(\{3, 99\}) =$ pos
  - $\alpha(\{-3, 2\}) = \top$

Second Step: Abstraction and Concretization Function

- Abstraction function (α) maps sets of concrete elements to the most precise value in the abstract domain
  - $\alpha(\{2, 10, 0\}) = \text{non-neg}$
  - $\alpha(\{3, 99\}) = \text{pos}$
  - $\alpha(\{-3, 2\}) = \top$
- Concretization function (γ) maps each abstract value to sets of concrete elements
  - $\gamma(\text{pos}) = \{x \mid x \in \mathbb{Z} \wedge x > 0\}$

Lattices and Abstract Domains

- Concretization function defines partial order on abstract values:

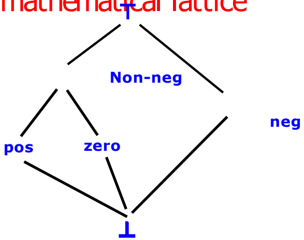
$$A_1 \leq A_2 \text{ iff } \gamma(A_1) \subseteq \gamma(A_2)$$

Lattices and Abstract Domains

- Concretization function defines partial order on abstract values:

$$A_1 \leq A_2 \text{ iff } \gamma(A_1) \subseteq \gamma(A_2)$$

- Furthermore, in an abstract domain, every pair of elements has a lub and glb $\Rightarrow$ mathematical lattice



- Least upper bound of two elements is called their join – useful for reasoning about control flow in programs

Almost Inverses

- Important property of the abstraction and concretization function is that they are almost inverses:

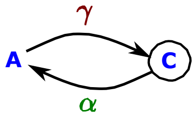
$$\alpha(\gamma(A)) = A$$

$$\begin{tikzcd} A \arrow[r, bend left, "\gamma"] & C \arrow[l, bend left, "\alpha"] \end{tikzcd}$$

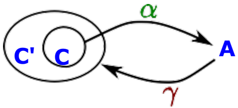
Almost Inverses

- Important property of the abstraction and concretization function is that they are almost inverses:

$$\alpha(\gamma(A)) = A$$



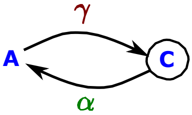
$$C \subseteq \gamma(\alpha(C))$$



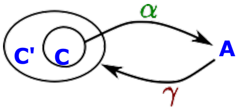
Almost Inverses

- Important property of the abstraction and concretization function is that they are almost inverses:

$$\alpha(\gamma(A)) = A$$



$$C \subseteq \gamma(\alpha(C))$$



- This is called a Galois insertion and captures the soundness of the abstraction

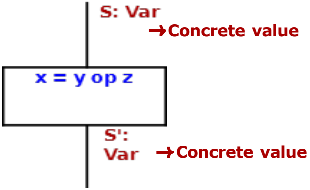
Step 3: Abstract Semantics

- Given abstract domain, α, γ, need to define abstract transformers (i.e., semantics) for each statement
    - Describes how statements affect our abstraction

Step 3: Abstract Semantics

- Given abstract domain, α, γ, need to define abstract transformers (i.e., semantics) for each statement
  - Describes how statements affect our abstraction
  - Abstract counter-part of operational semantics rules

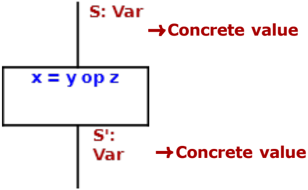
Operational Semantics



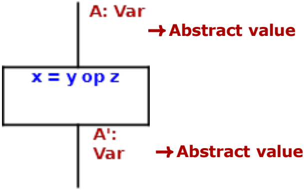
Step 3: Abstract Semantics

- Given abstract domain, α, γ, need to define abstract transformers (i.e., semantics) for each statement
  - Describes how statements affect our abstraction
  - Abstract counter-part of operational semantics rules

Operational Semantics



Abstract Semantics



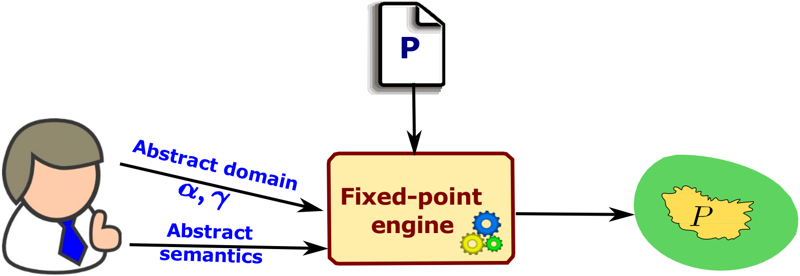
Back to Our Example

- For our sign analysis, we can define abstract transformer for x = y + z as follows:

	pos	neg	zero	non-neg	⊤	⊥
pos	pos	⊤	pos	pos	⊤	⊥
neg	⊤	neg	neg	⊤	⊤	⊥
zero	pos	neg	zero	non-neg	⊤	⊥
non-neg	pos	⊤	non-neg	non-neg	⊤	⊥
⊤	⊤	⊤	⊤	⊤	⊤	⊥
⊥	⊥	⊥	⊥	⊥	⊥	⊥

- To ensure soundness of static analysis, must prove that abstract semantics faithfully models concrete semantics

Putting It All Together

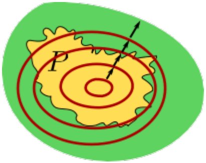


Fixed-point Computations

- Fixed-point computation: Repeated symbolic execution of the program using abstract semantics until our approximation of the program reaches an equilibrium

Fixed-point Computations

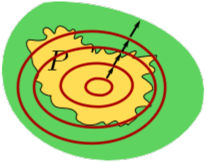
- Fixed-point computation: Repeated symbolic execution of the program using abstract semantics until our approximation of the program reaches an equilibrium
- Least fixed-point: Start with underapproximation and grow the approximation until it stops growing



Fixed-point Computations

- Fixed-point computation: Repeated symbolic execution of the program using abstract semantics until our approximation of the program reaches an equilibrium

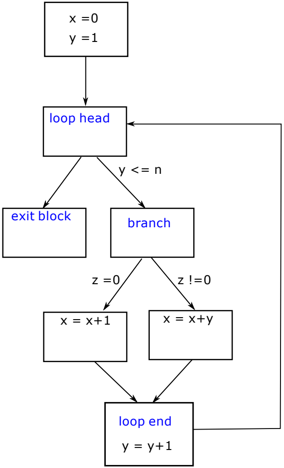
- Least fixed-point: Start with underapproximation and grow the approximation until it stops growing



- Assuming correctness of your abstract semantics, the least fixed point is an overapproximation of the program!

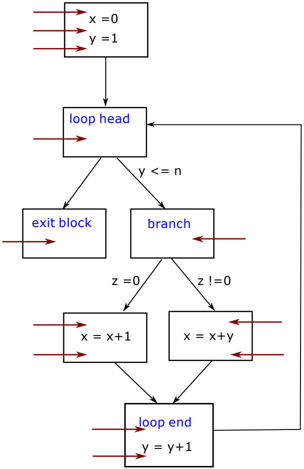
Performing Least Fixed Point Computation

- Represent program as a control-flow graph



Performing Least Fixed Point Computation

- Represent program as a control-flow graph
- Want to compute abstract values at every program point

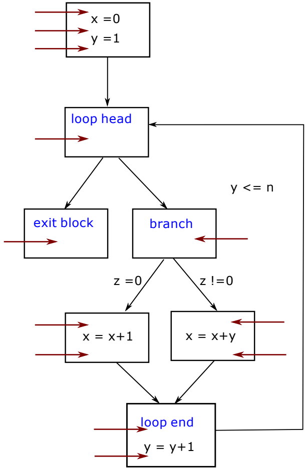


Performing Least Fixed Point Computation

- Represent program as a control-flow graph

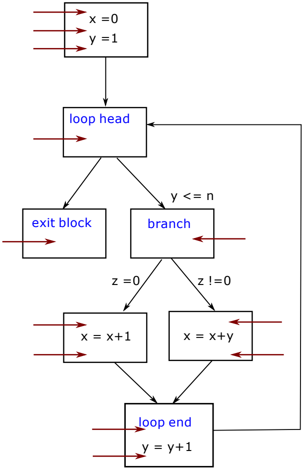
- Want to compute abstract values at every program point

- Initialize all abstract states to $\perp$



Performing Least Fixed Point Computation

- Represent program as a control-flow graph
- Want to compute abstract values at every program point
- Initialize all abstract states to $\perp$
- Repeat until no abstract state changes at any program point:

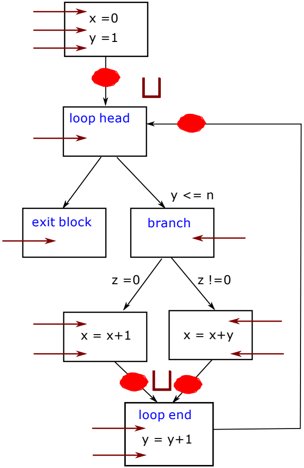


Performing Least Fixed Point Computation

- Represent program as a control-flow graph

- Want to compute abstract values at every program point

- Initialize all abstract states to $\perp$
- Repeat until no abstract state changes at any program point:
  - Compute abstract state on entry to a basic block B by taking the join of B's predecessors

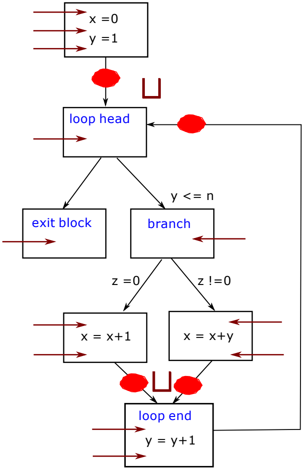


Performing Least Fixed Point Computation

- Represent program as a control-flow graph

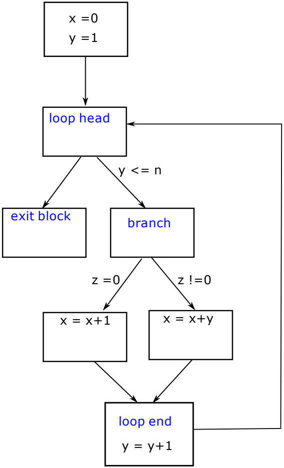
- Want to compute abstract values at every program point

- Initialize all abstract states to $\perp$
- Repeat until no abstract state changes at any program point:
  - Compute abstract state on entry to a basic block B by taking the join of B's predecessors
  - Symbolically execute each basic block using abstract semantics



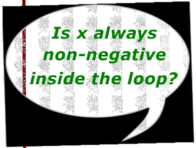
An Example

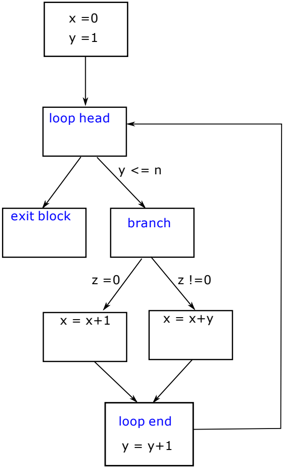
```
x = 0;
y =0;

while(y <= n)
{
  if (z == 0)
    { x = x+1;
  }
  else {
    x = x + y;
  }
  y = y+1
}
```



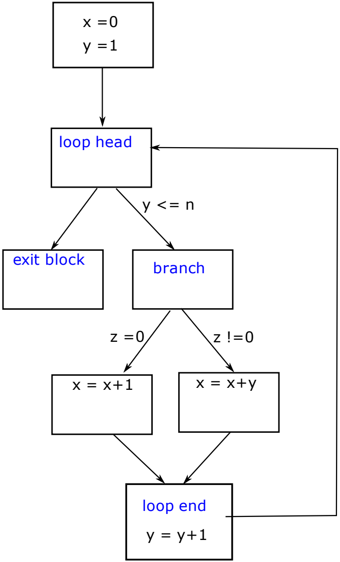
An Example

```
x = 0;
y =0;

while(y <= n)
{
   if (z == 0)
      { x = x+1;
   }
   else {
      x = x + y;
   }
   y = y+1
}
```

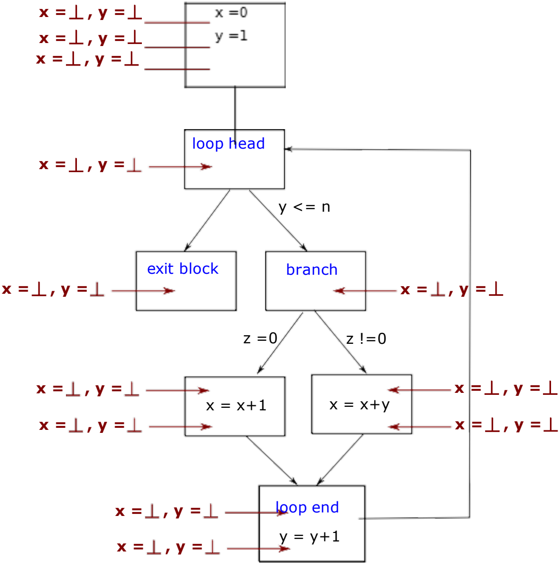




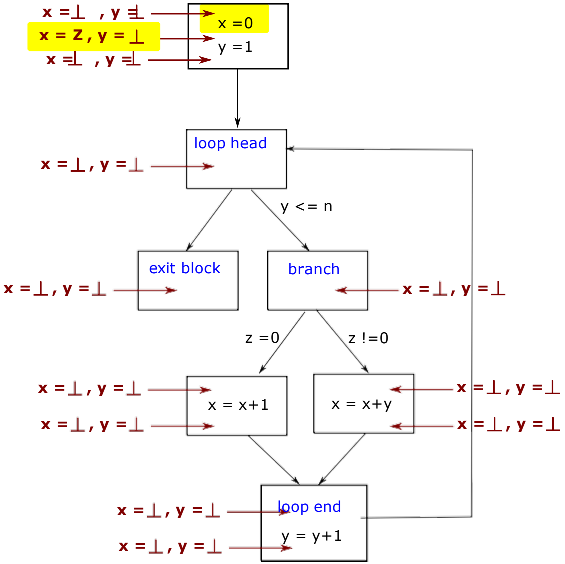
Fixed-Point Computation



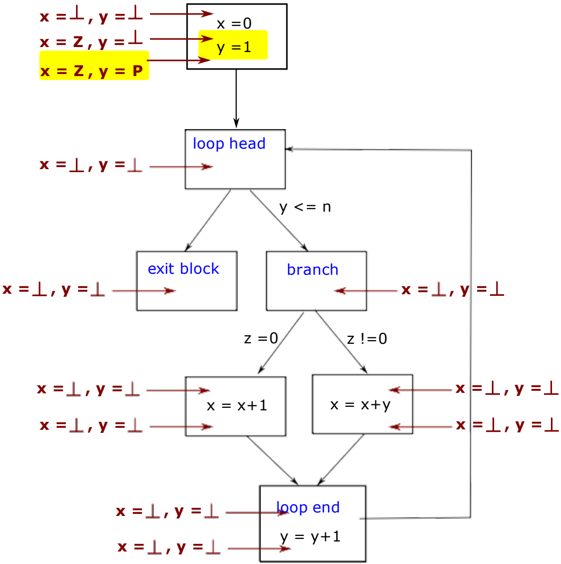
Fixed-Point Computation



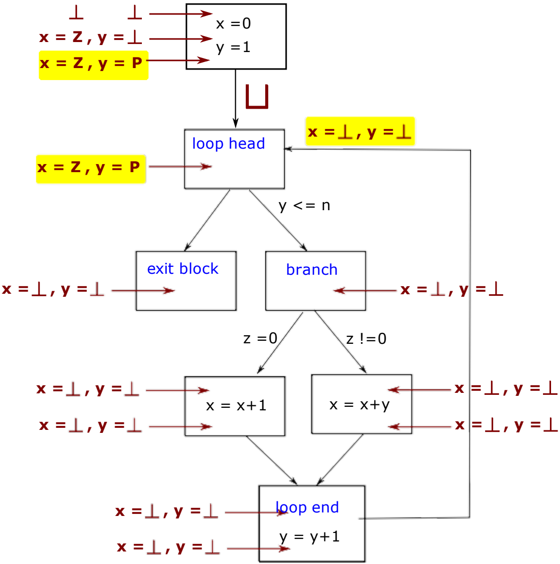
Fixed-Point Computation



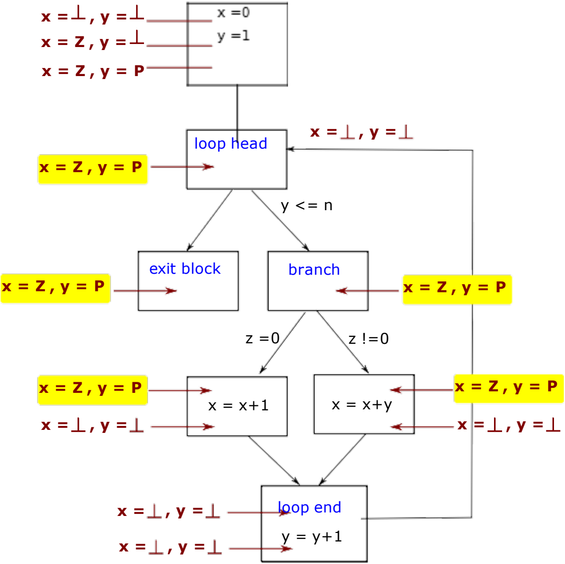
Fixed-Point Computation



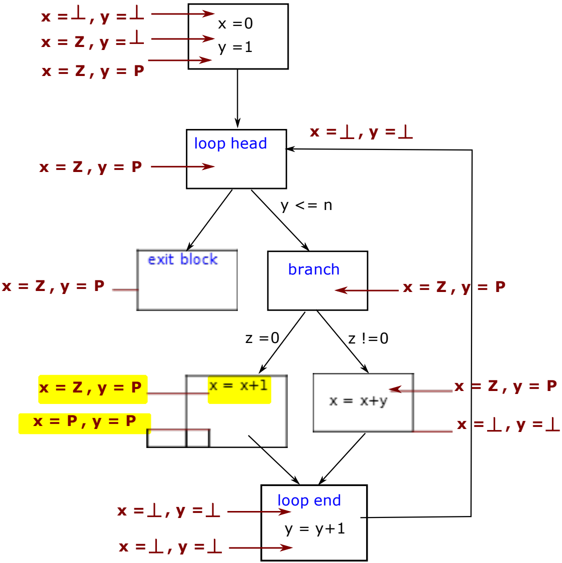
Fixed-Point Computation



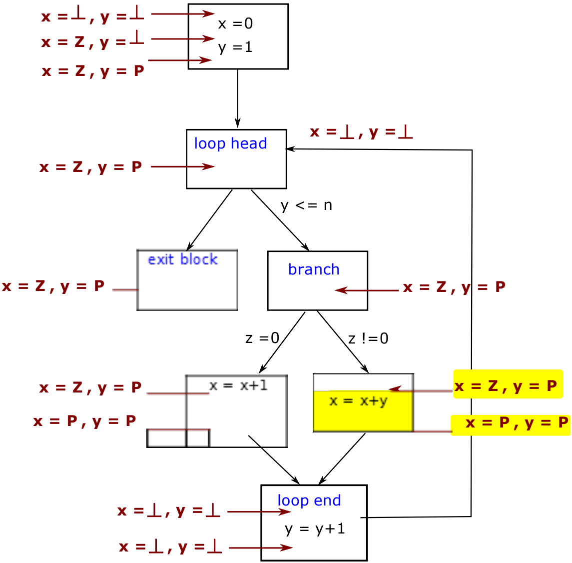
Fixed-Point Computation



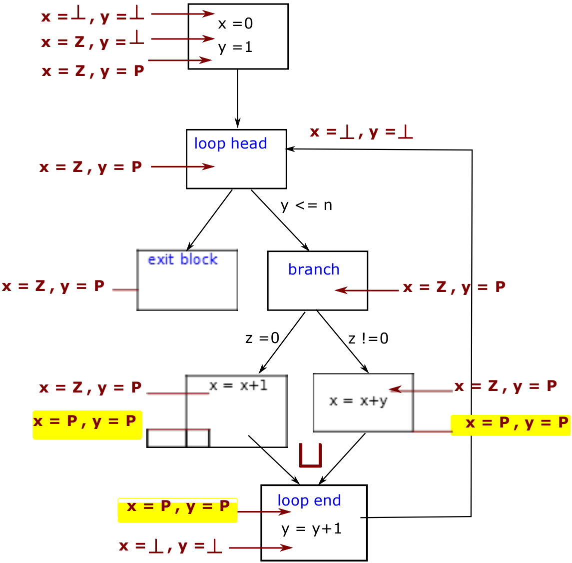
Fixed-Point Computation



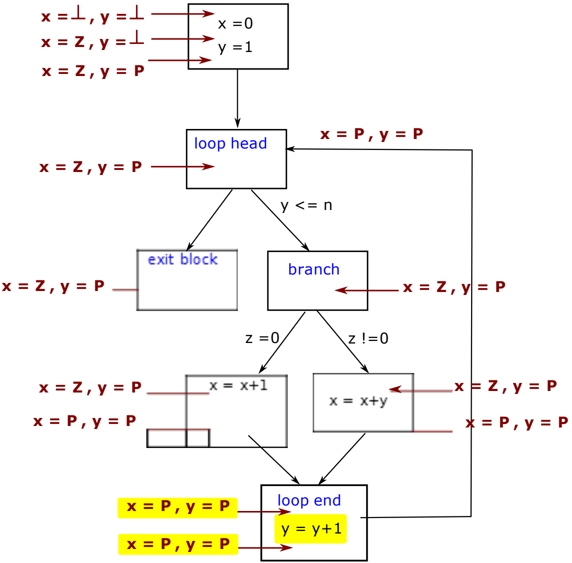
Fixed-Point Computation



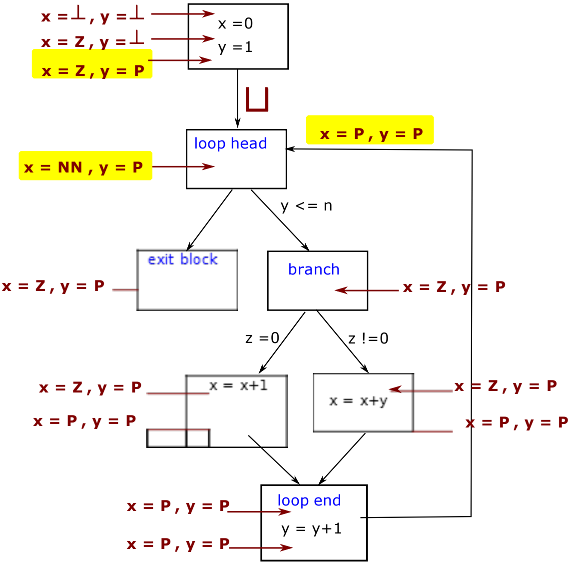
Fixed-Point Computation



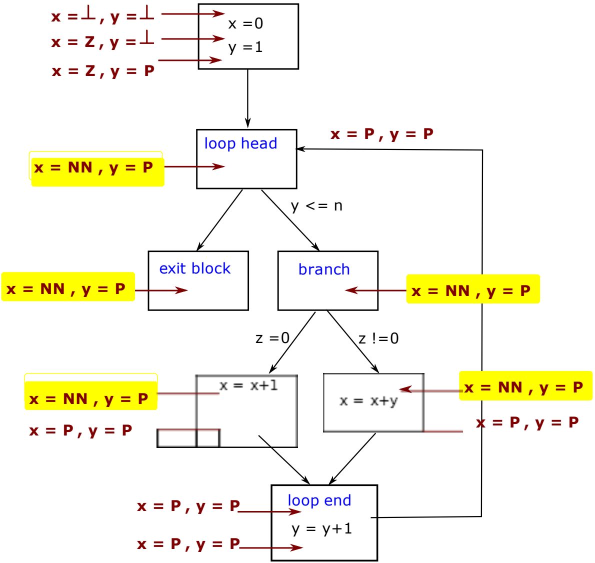
Fixed-Point Computation



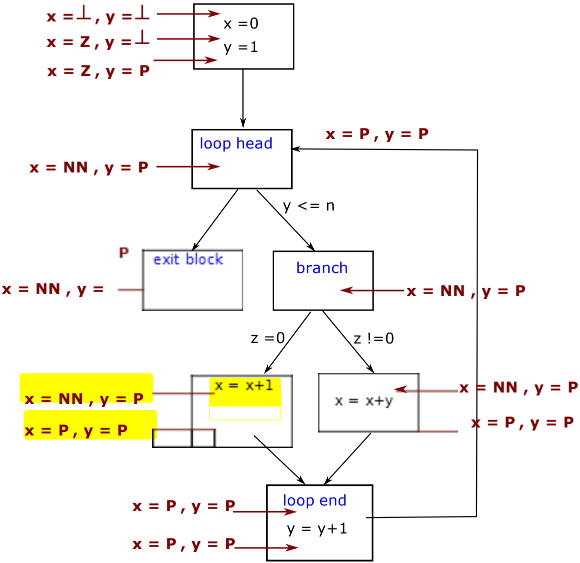
Fixed-Point Computation



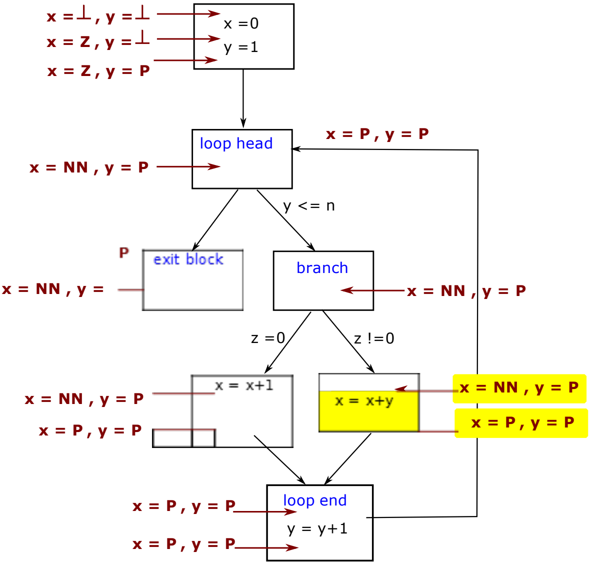
Fixed-Point Computation



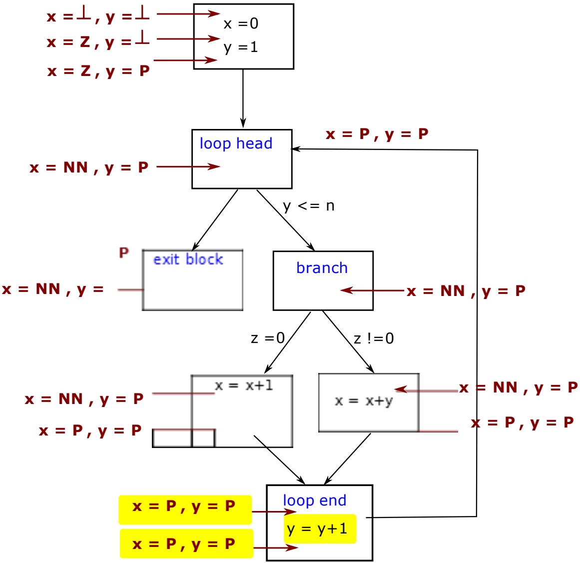
Fixed-Point Computation



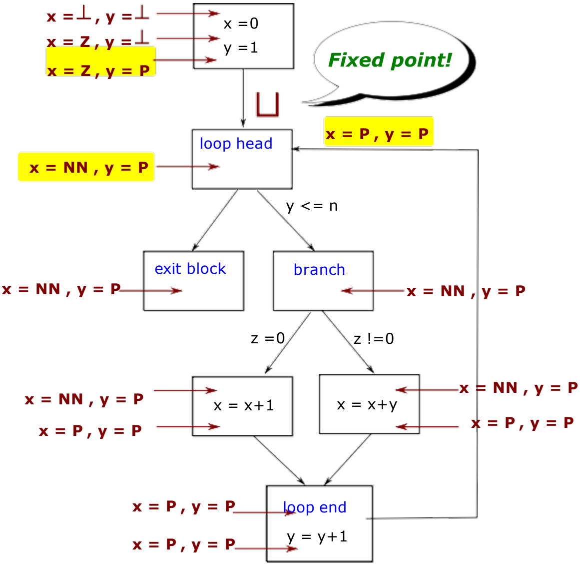
Fixed-Point Computation



Fixed-Point Computation



Fixed-Point Computation



Termination of Fixed-Point Computation

- In this example, we quickly reached least fixed point – but does this computation always terminate?

Termination of Fixed-Point Computation

- In this example, we quickly reached least fixed point – but does this computation always terminate?
  - Yes, assuming abstract domain forms complete lattice

Termination of Fixed-Point Computation

- In this example, we quickly reached least fixed point – but does this computation always terminate?
  - Yes, assuming abstract domain forms complete lattice
  - This means every subset of elements (including infinite subsets) have a LUB

Termination of Fixed-Point Computation

- In this example, we quickly reached least fixed point – but does this computation always terminate?
  - Yes, assuming abstract domain forms complete lattice
  - This means every subset of elements (including infinite subsets) have a LUB
- Unfortunately, many interesting domains do not have this property, so we need widening operators for convergence.

Lessons To Take Away

- Considered only one static analysis approach, but illustrates two key ideas underlying program analysis:
  - Abstraction: Only reason about certain properties of interest

Lessons To Take Away

- Considered only one static analysis approach, but illustrates two key ideas underlying program analysis:
  - Abstraction: Only reason about certain properties of interest
  - Fixed-point computation: Allows us to obtain sound overapproximation of the program

Lessons To Take Away

- Considered only one static analysis approach, but illustrates two key ideas underlying program analysis:
  - Abstraction: Only reason about certain properties of interest
  - Fixed-point computation: Allows us to obtain sound overapproximation of the program
- But many static analyses also differ in several ways:
  - Flow (in)sensitivity: Some analyses only compute facts for the whole program, not for every program point

Lessons To Take Away

- Considered only one static analysis approach, but illustrates two key ideas underlying program analysis:
  - Abstraction: Only reason about certain properties of interest
  - Fixed-point computation: Allows us to obtain sound overapproximation of the program
- But many static analyses also differ in several ways:
  - Flow (in)sensitivity: Some analyses only compute facts for the whole program, not for every program point
  - Path sensitivity: More precise analyses compute different facts for different program paths

Challenges and Open Problems

Many open problems

- Precise and scalable heap reasoning
- Concurrency
- Dealing with open programs
- Modular program analysis