Check-in

Review: Dataflow

Give an example of a forward dataflow analysis and an example of a backward dataflow analysis.

forward: constant propagation

backwards: live variable analysis / dead code elimination

Announcements

Review: Dataflow

P6 : due last night

P7 : out now, oracle out now

```
main : () -> void {
toconsole        <;
}
```

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EECS 665 COMPILER CONSTRUCTION

Abstract Interpretation

Previously…

Review: Dataflow

Global Dataflow analysis

- Intuition
- Operations

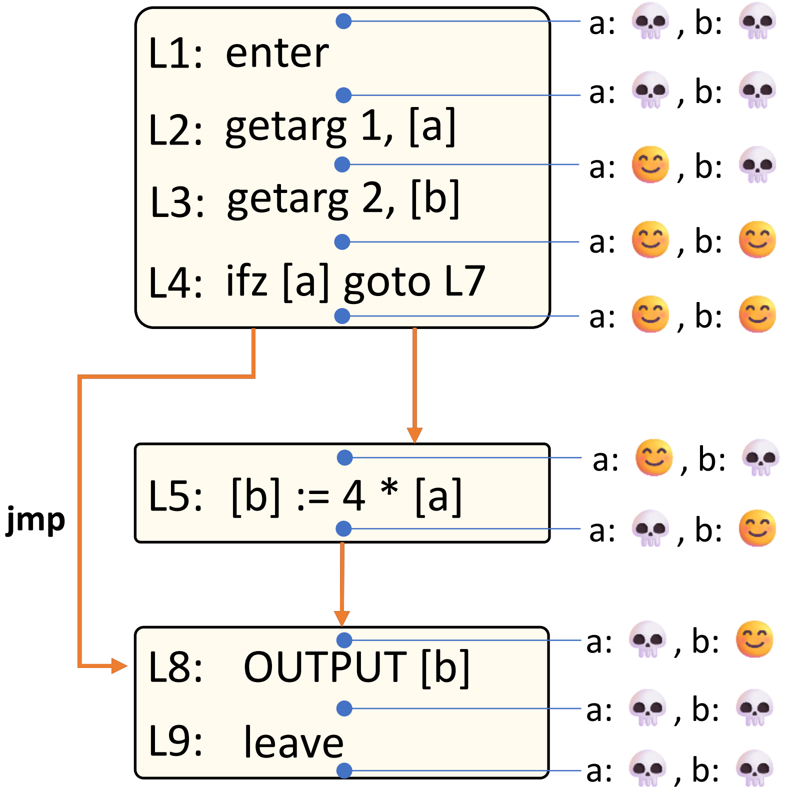
You should know

- The basic concepts of dataflow facts
  - Backwards and Forward analysis
  - Augment local analysis with “IN” and “OUT” sets
  - You need to merge fact sets

Optimization

Merging Fact Sets

Dataflow Intuition



Fact sets may be different when multiple successors/predecessors join

- Need to merge incoming fact sets

Merge as conservatively as possible

- Don’t do anything without a guarantee!
- Plan for all possible flows

Example: is L3 live? *(consider both block paths)*

- L3 definition clobbered on the fallthrough branch (at L5)
- L3 definition not clobbered on the jump branch

Today's Outline

IR Optimization

Rounding out dataflow analysis concepts

- Some more examples
- Considering more complex code
- Dataflow Framework

Abstract Interpretation

- Concepts
- Examples

Optimization

Refresh Constant/Copy Propagation

Copy Propagation

- Replace RHS of simple assigns with value of assign (if known)
- Forward analysis

```
x := 1
y := x
z := x + y
x := 3
```

→

```
x := 1
y := 1
z := 1 + 1
x := 3
```

Constant folding

- Replace constant RHS expressions with value
- Traversal order isn’t important

```
x := 1
y := 1
z := 1 + 1
x := 3
```

→

```
x := 1
y := 1
z := 2
x := 3
```

Example Analyses

Dataflow: Formalization

Dead Code Elimination

- Backwards analysis
- Fact sets: the liveness of each variable

Known Live	Known Dead	Not Enough Info
😊	💀	🤷

- Merge:

😊 ∪ 💀 = 😊

😊 ∪ 🤷 = 😊

💀 ∪ 🤷 = 🤷

Constant Propagation

- Forward analysis
- Fact sets: the known value of each variable

Set of Known Values	Not Enough Info
{<value>, <value2}, …	🤷

- Merge:

Set Union

{ 1 } ∪ { 1,2 } = { 1,2 }

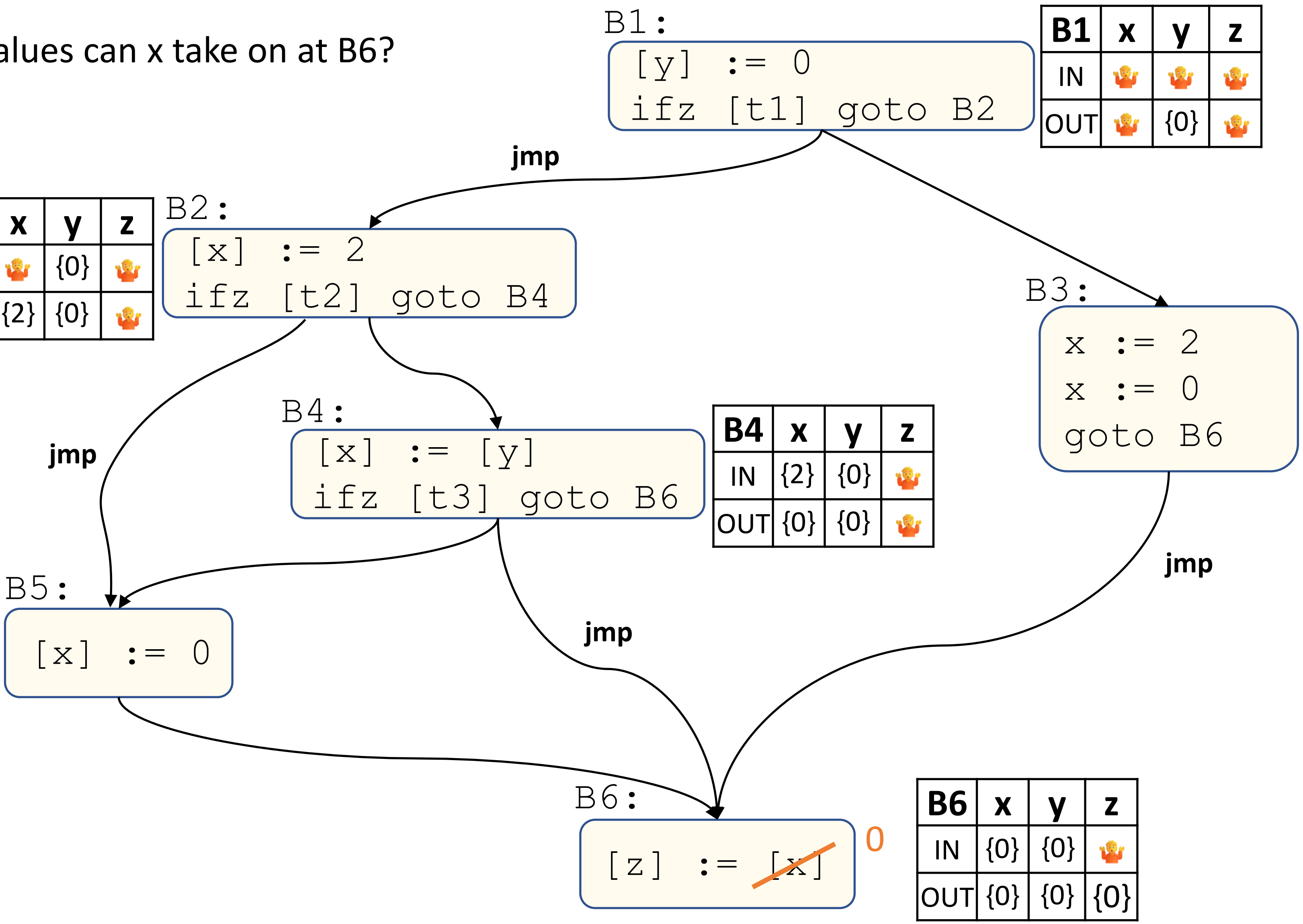
…except

{ * } ∪ 🤷 = 🤷

Example Constant Propagation

Dataflow: Formalization - Example

What values can x take on at B6?



B1	x	y	z
IN	🤷	🤷	🤷
OUT	🤷	{0}	🤷

B2	x	y	z
IN	🤷	{0}	🤷
OUT	{2}	{0}	🤷

B3	x	y	z
IN	🤷	{0}	🤷
OUT	{0}	{0}	🤷

B4	x	y	z
IN	{2}	{0}	🤷
OUT	{0}	{0}	🤷

B5	x	y	z
IN	{0,2}	{0}	🤷
OUT	{0}	{0}	🤷

B6	x	y	z
IN	{0}	{0}	🤷
OUT	{0}	{0}	{0}

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Optimization

Handling Practical Programs

Global Dataflow: Formalization

Global variables

- We only have visibility into 1 procedure
- Be conservative about the effect of other procedures
  - Reset fact sets across a call
  - Consider global variables live at function end

Analysis Termination
Dataflow: Formalization

In the previous examples, we completed in one pass over the CFG

- This won’t always be the case, due to a fundamental construct…

Analysis Termination

In the previous examples, we completed in one pass over the CFG

- This won't always be the case, due to a fundamental construct… loops
- Loops (specifically back edges) create cyclic dependencies

Oh bröther, you might have some lööps

Loops: Dependency cycles

Dataflow: Formalization

Solution: Saturate fact sets

- Start sets "TBD" (🤷) value
- Run the algorithm until sets don't change

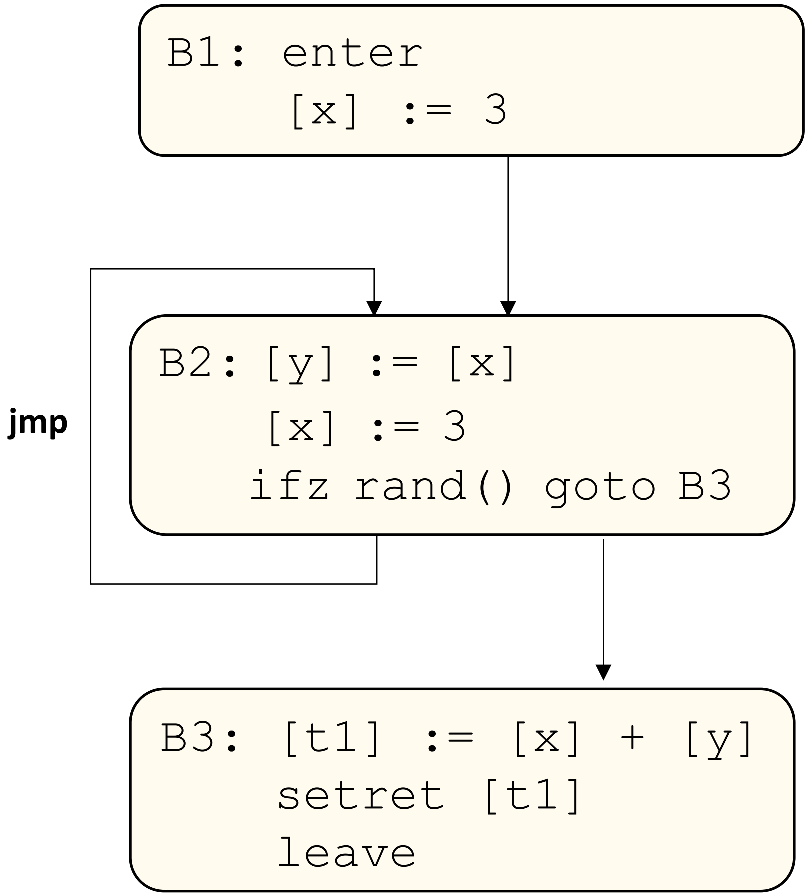
We've seen the saturation approach before

- (FIRST and FOLLOW sets)

Constant propagation

IN(B2) requires knowing OUT(B2)

OUT(B2) requires knowing IN(B2)



B1	x	y
IN	🤷	🤷
OUT	🤷	🤷

B1	x	y
IN	🤷	🤷
OUT	{3}	🤷

B1	x	y
IN	🤷	🤷
OUT	{3}	🤷

B2	x	y
IN	🤷	🤷
OUT	🤷	🤷

B2	x	y
IN	🤷	🤷
OUT	{3}	🤷

B2	x	y
IN	{3}	🤷
OUT	{3}	{3}

B3	x	y
IN	🤷	🤷
OUT	🤷	🤷

B3	x	y
IN	{3}	🤷
OUT	{3}	🤷

B3	x	y
IN	{3}	{3}
OUT	{3}	{3}

Handling Practical Data Abstractions

Global Dataflow: Formalization

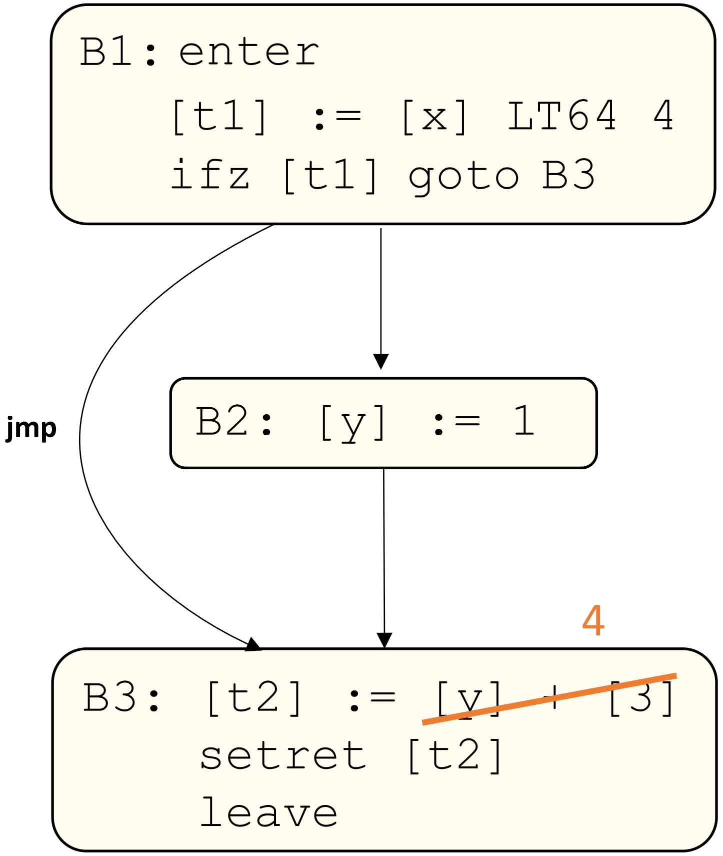
Undefined Behavior

```
int main(){
  int x,y;
  if (x == 4){
    y = 1;
  }
  return y + 3;
}
```

- Could we fold y + 3?

  Ain't no law against it!

Would need to have types of unknowns



B1	x	y
IN	🤷	🤷
OUT	🤷	🤷

B2	x	y
IN	🤷	🤷
OUT	🤷	🤷

B2	x	y
IN	🤷	🤷
OUT	🤷	{1}

B1	x	y
IN	🤷	🤷
OUT	🤷	🤷

B1	x	y
IN	🤷	{1}
OUT	🤷	{1}

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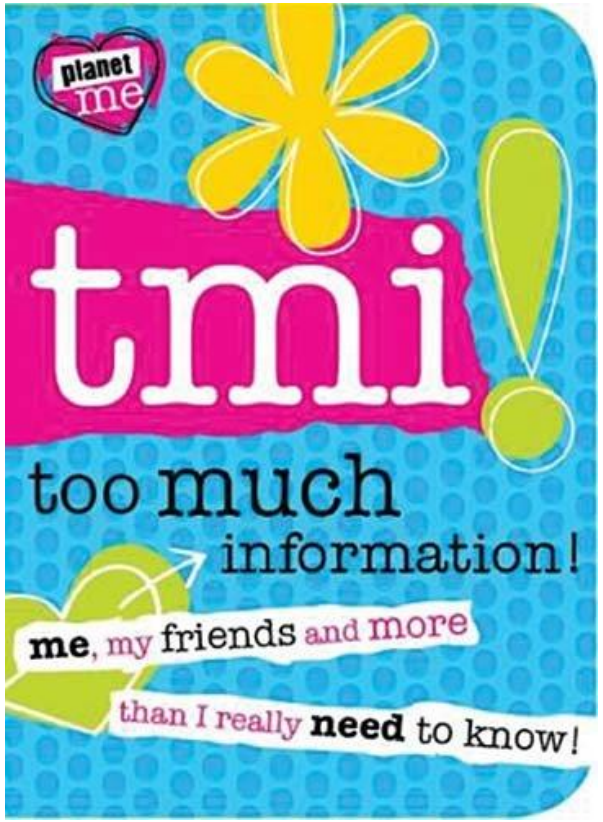
Optimization

Complicated Fact Sets

Dataflow: Formalization

Occasionally, fact sets exceed their usefulness, e.g.:

- Constant propagation: once we have > 1 value in a set, we don't really care what the values are
- Change the domain of values to match what we can learn / use in analysis



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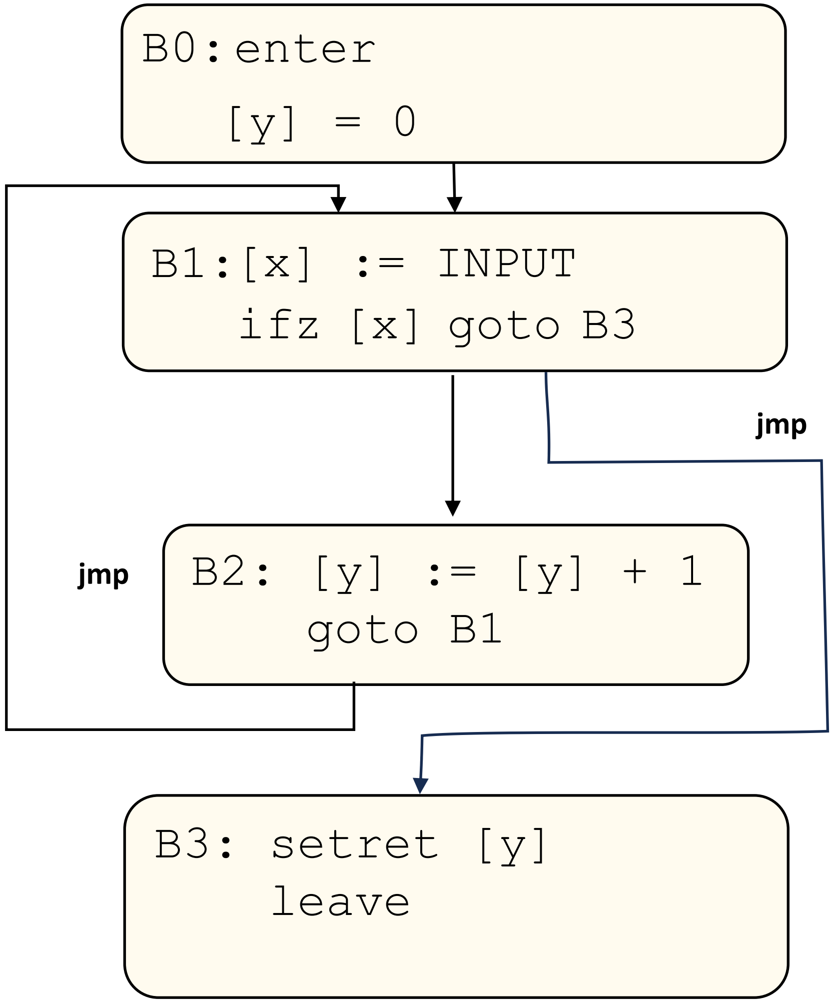


B0	x	y
IN	🤷	🤷
OUT	🤷	🤷

B1	x	y
IN	🤷	🤷
OUT	🤷	🤷

B2	x	y
IN	🤷	🤷
OUT	🤷	🤷

B3	x	y
IN	🤷	🤷
OUT	🤷	🤷

Complicated Fact Sets

Dataflow: Formalization

Occasionally, fact sets exceed their usefulness, e.g.:

- Constant propagation: once we have > 1 value in a set, we don't really care what the values are
- Change the domain of values to match what we can learn / use in analysis

Before

Set of Known Values	We Don't Know
{1}, {1,2}, …	🤷

After

Single Constant Value	We Don't Know	Could be Anything
1, 2, 3, …	⊥ 🤷	T 🤷

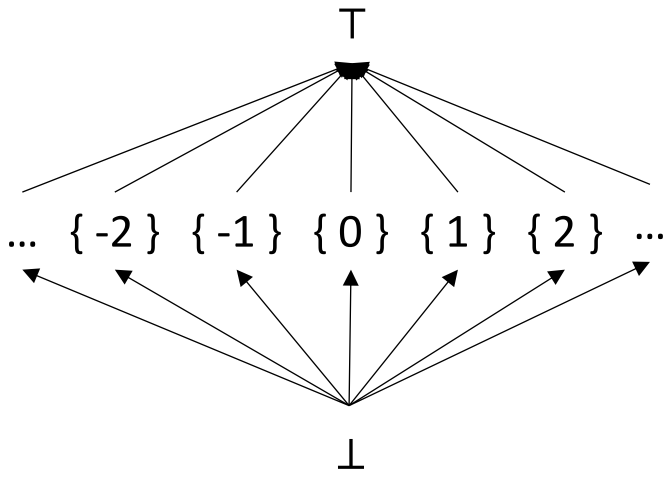
Allows "ranking" fact sets

Ranking Fact Sets

Dataflow: Formalization

Values form a *lattice*

Values merge *to their least upper bound*



Before

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{1}, {1,2}, …	🤷

After

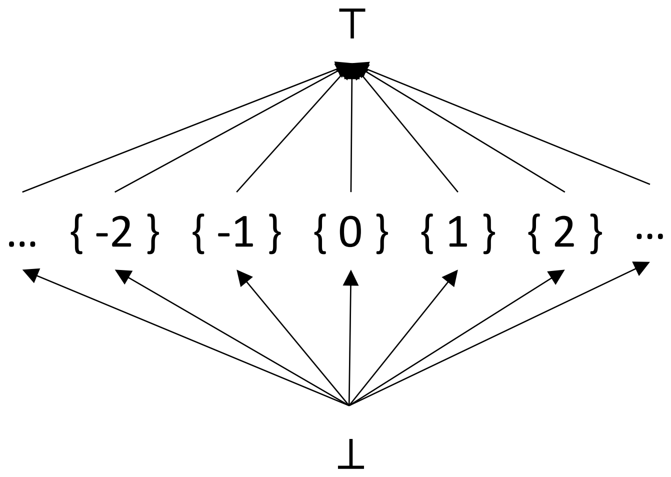
Single Constant Value	We Don't Know	Could be Anything
1, 2, 3, …	⊥ ~~🤷~~	⊤ ~~🤷~~

Reaching a Fixpoint

Dataflow: Formalization

Values form a *lattice*

Values merge *to their least upper bound*

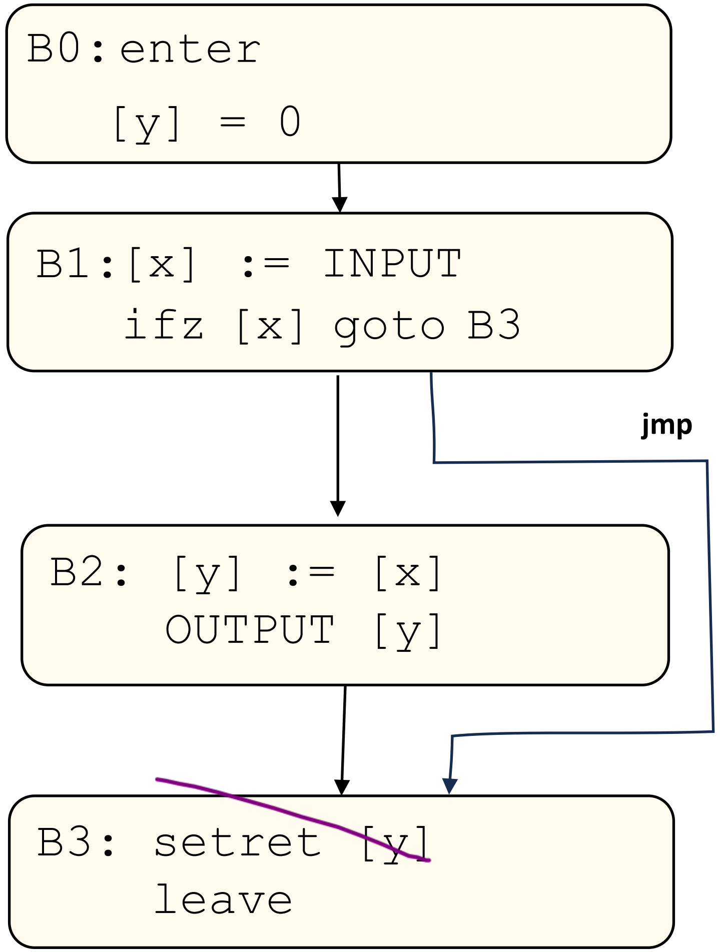


When the lattice has a finite size:

- Guarantees termination of the analysis
  - Merges are monotonically non-decreasing
  - Local steps add finite element from the lattice
  - Stop when no set grows

Incorporating Predicates

Dataflow: Formalization



B0	x	y
IN	⊥	⊥
OUT	⊥	⊥

B1	x	y
IN	⊥	⊥
OUT	⊥	⊥

B2	x	y
IN	⊥	⊥
OUT	⊥	⊥

B3	x	y
IN	⊥	⊥
OUT	⊥	⊥

Summary
IR Optimization

Covered some key optimization concepts

- Inter-block (global) analysis
- Dataflow frameworks:
  - Define fact sets and how they interact

Next Time – Static Single Assignment (SSA)

- A program form that eases and enhances optimization