Program Analysis

12. Selective X-sensitivity

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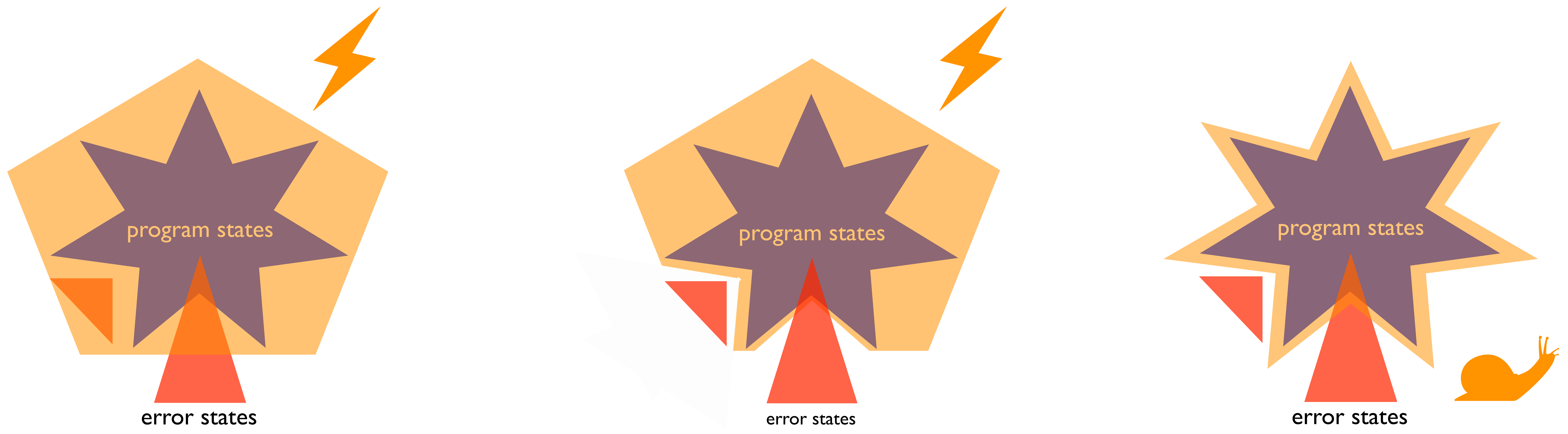
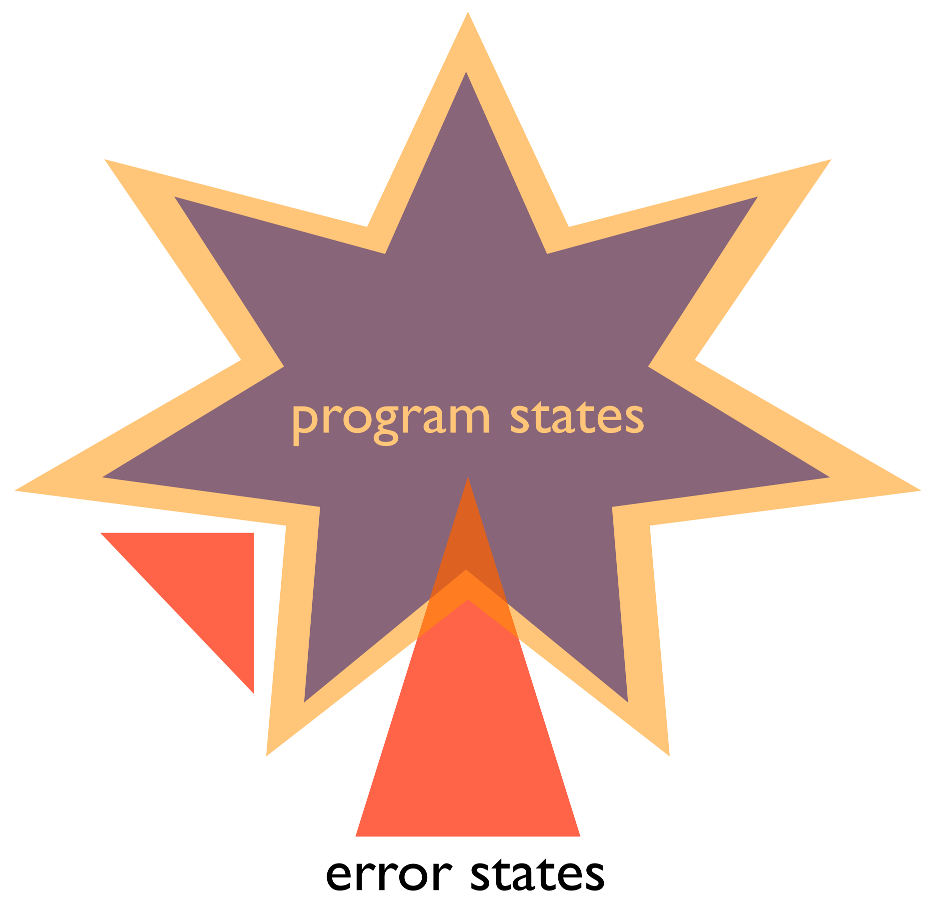
Cost-Accuracy Balance

- How to **strike a balance** between cost and accuracy?
- How to find a **minimal abstraction** to produce the **best result**?



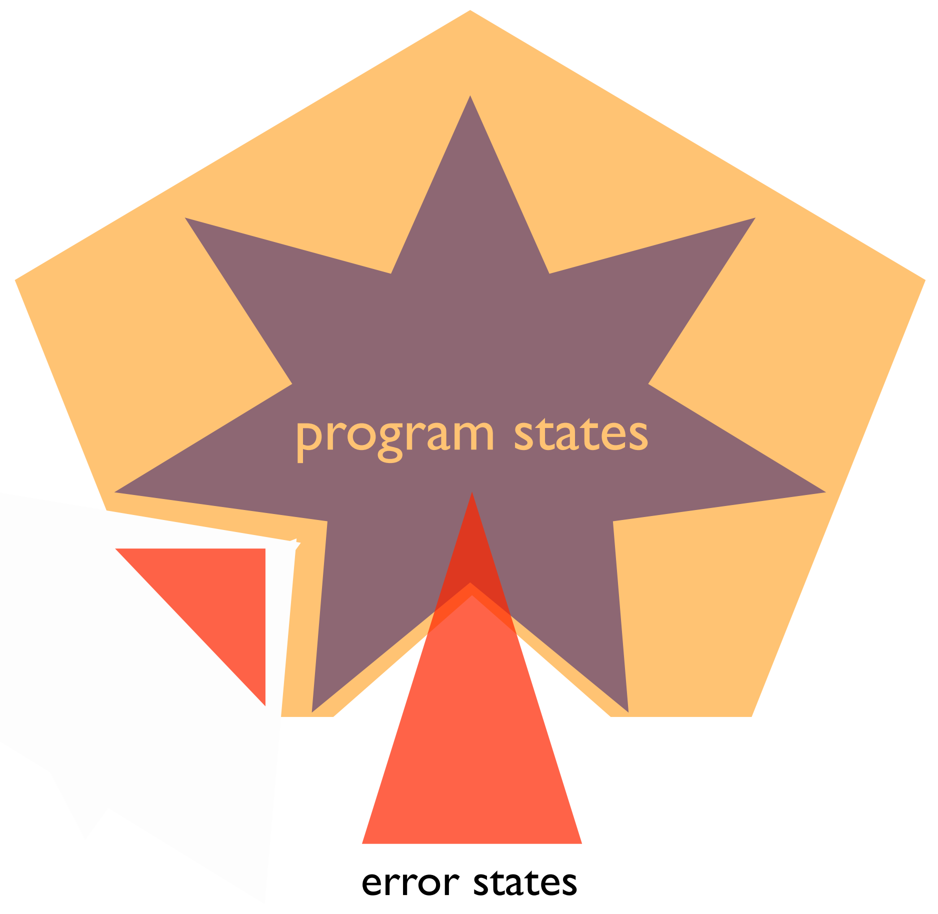
Selective X-Sensitivity

- Selectively apply a precision-improving technique X-sensitivity
    - only when/where it matters
    - X : context, flow, variable relationship, etc



Uniform (3-CFA)
False alarm 24%↓/ Overhead 1300%↑

vs
(context-sensitivity)



Selective
False alarms 24%↓/ Overhead 28%↑

*Oh et al. Selective Context-Sensitivity Guided by Impact Pre-analysis, PLDI'14

Example: Context-Sensitivity

- Suppose an analysis with the interval domain

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
5:   g();
6:   g();
   }
```

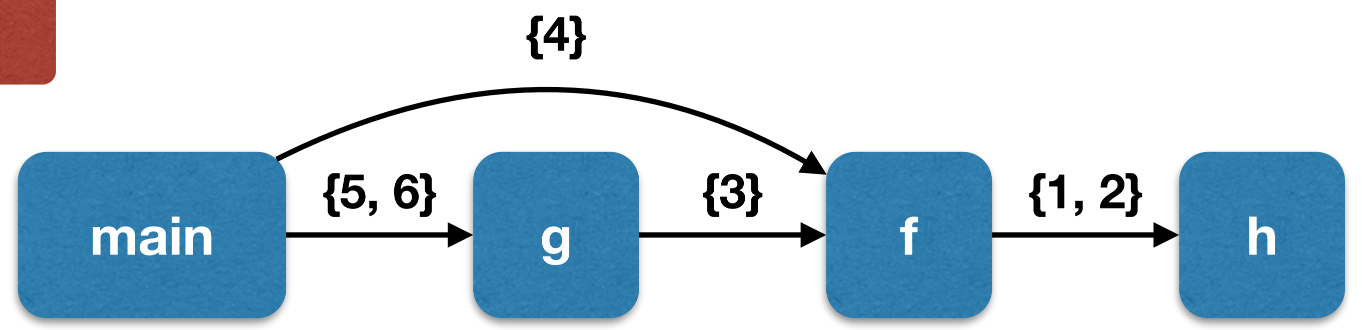
Example: Context-Sensitivity

- Context-insensitive analysis

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
5:   g();
6:   g();
   }
```

[-oo, +oo]

cannot prove



Example: Context-Sensitivity

- Uniformly context-sensitive analysis (3-CFA)

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
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```

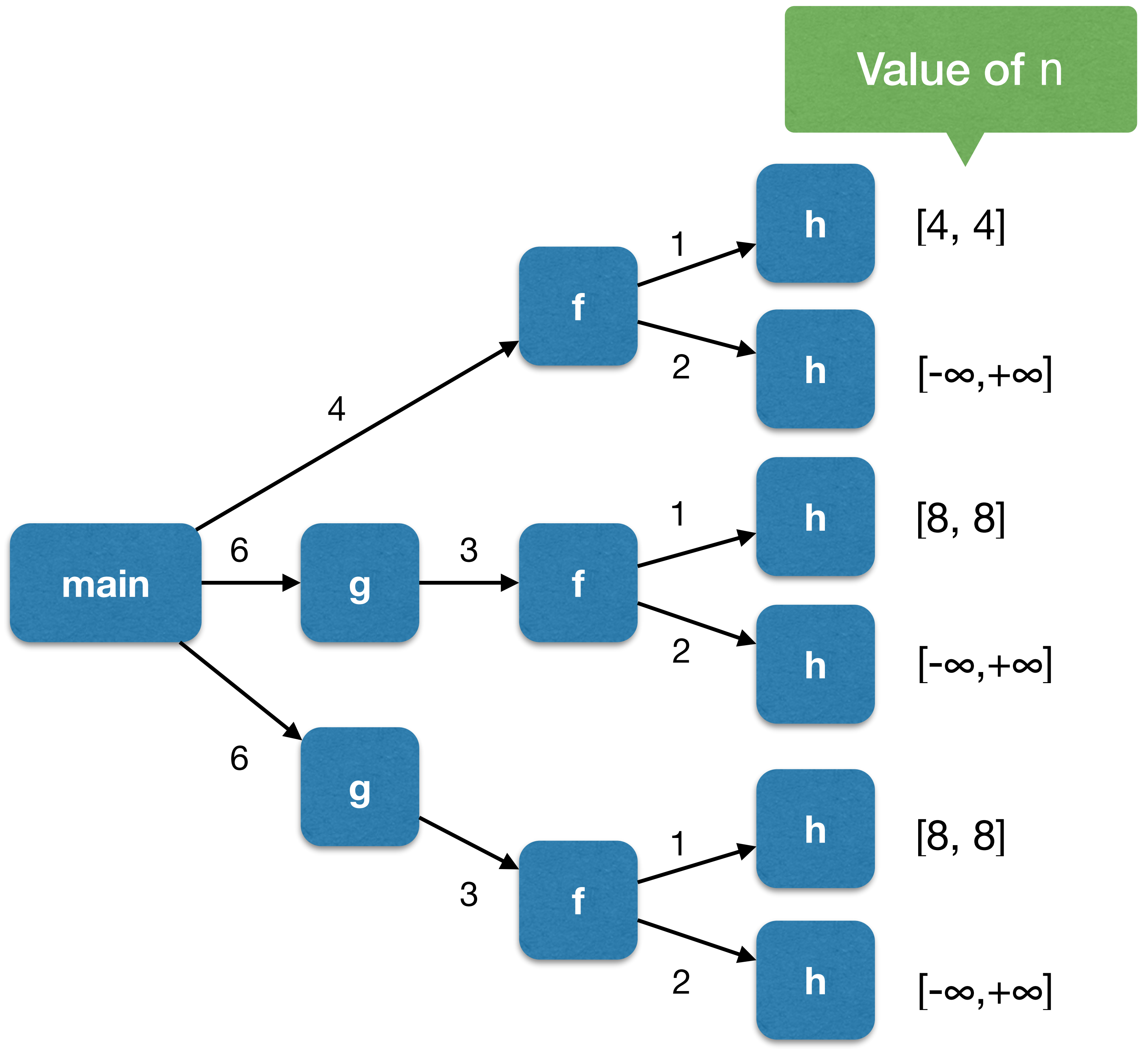

Example: Context-Sensitivity

- Uniformly context-sensitive analysis (3-CFA)

Proved!

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
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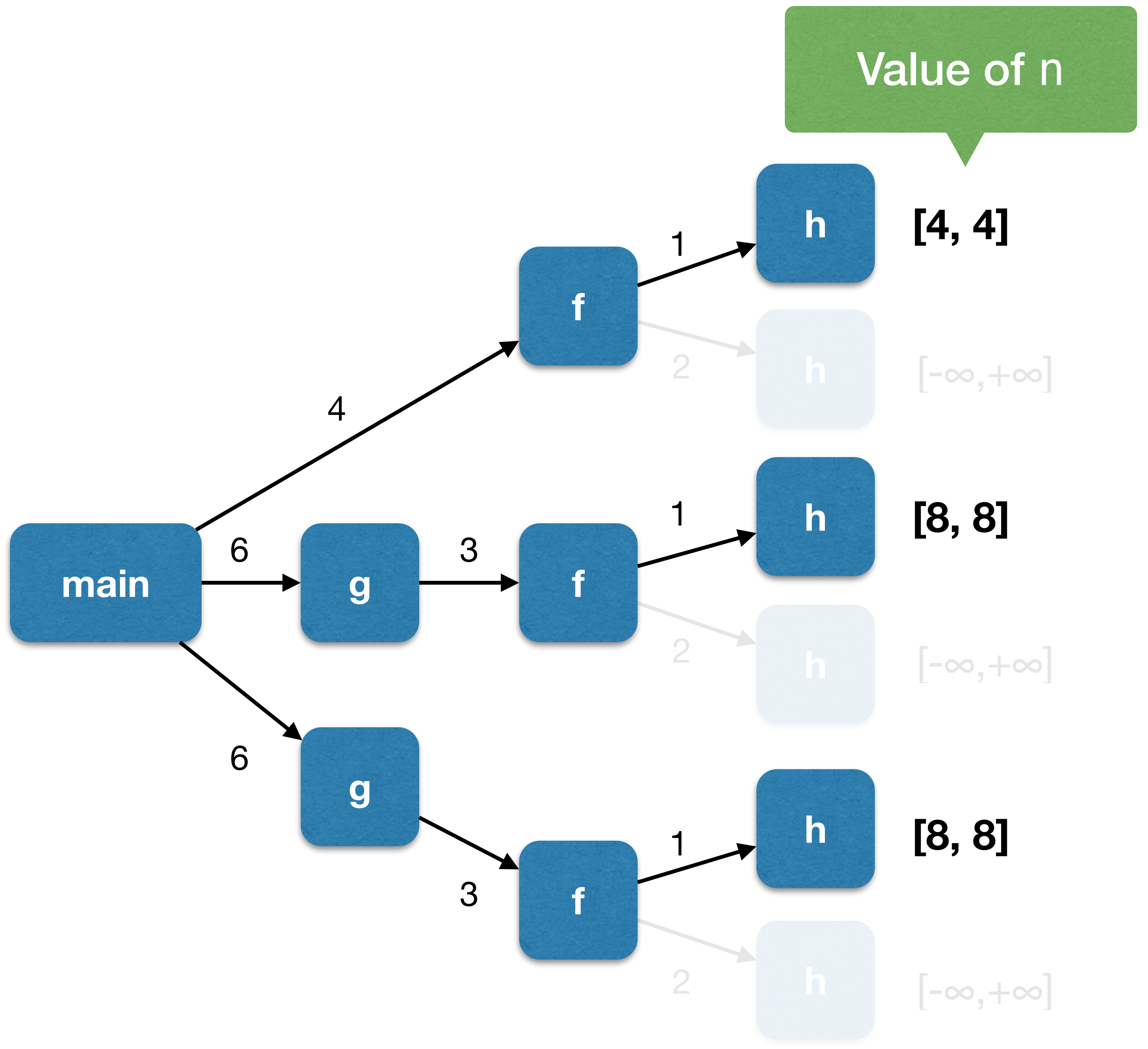

Example: Context-Sensitivity

- Problem of uniformly sensitive analysis

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
5:   g();
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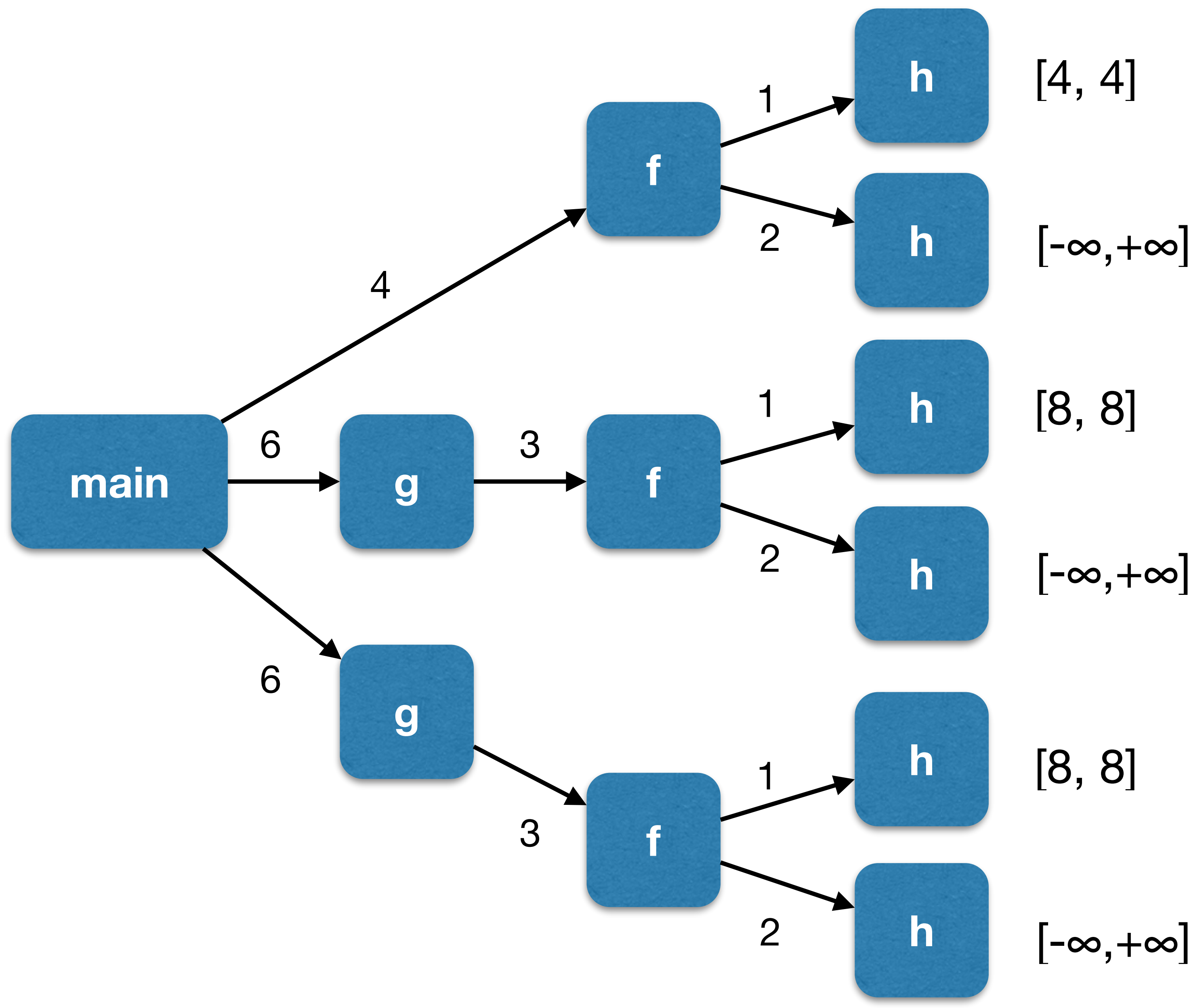
```



Example: Context-Sensitivity

- Problem of uniformly sensitive analysis 1: useless sensitivity

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
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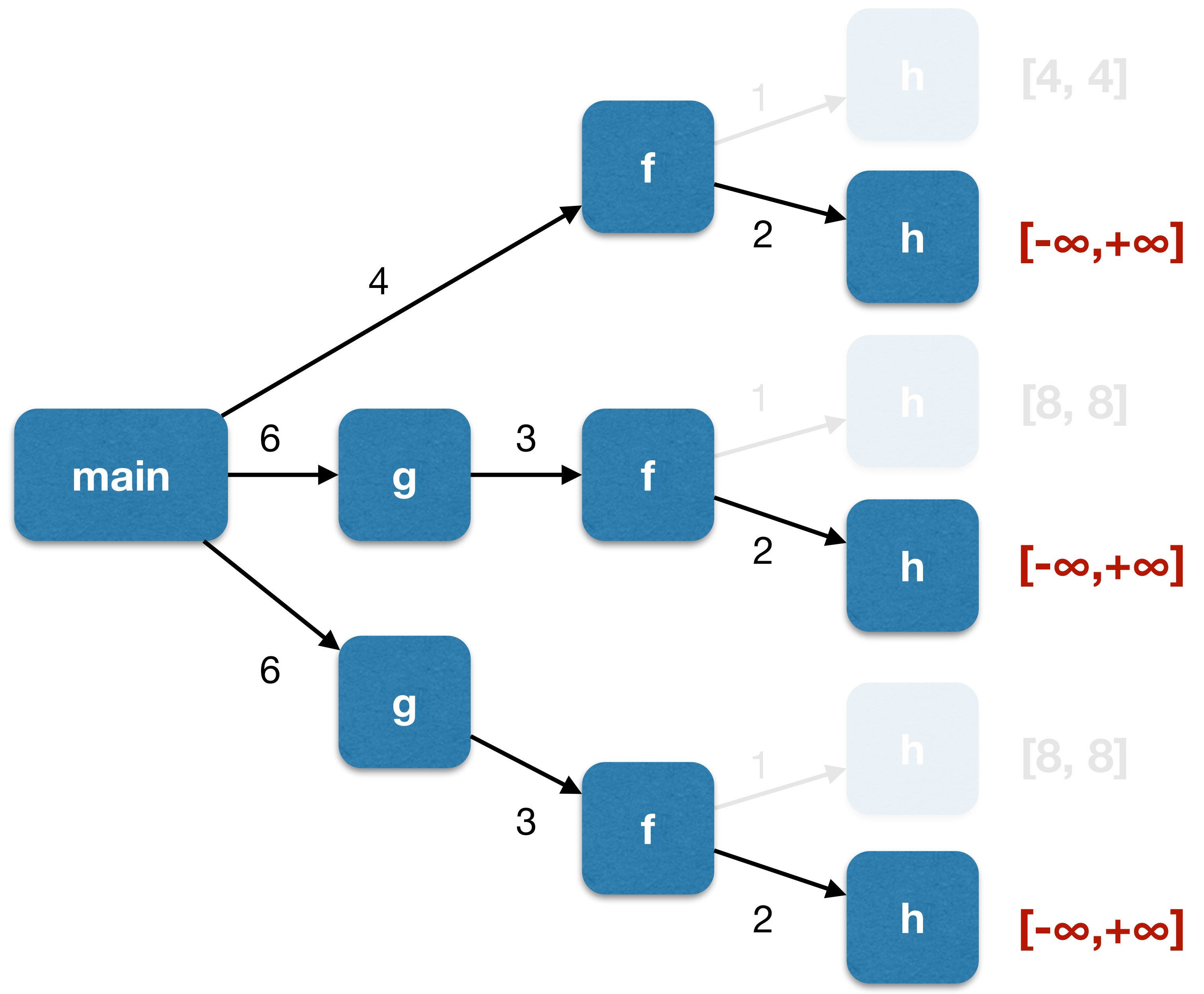
```



Example: Context-Sensitivity

- Problem of uniformly sensitive analysis 2: too much sensitivity

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
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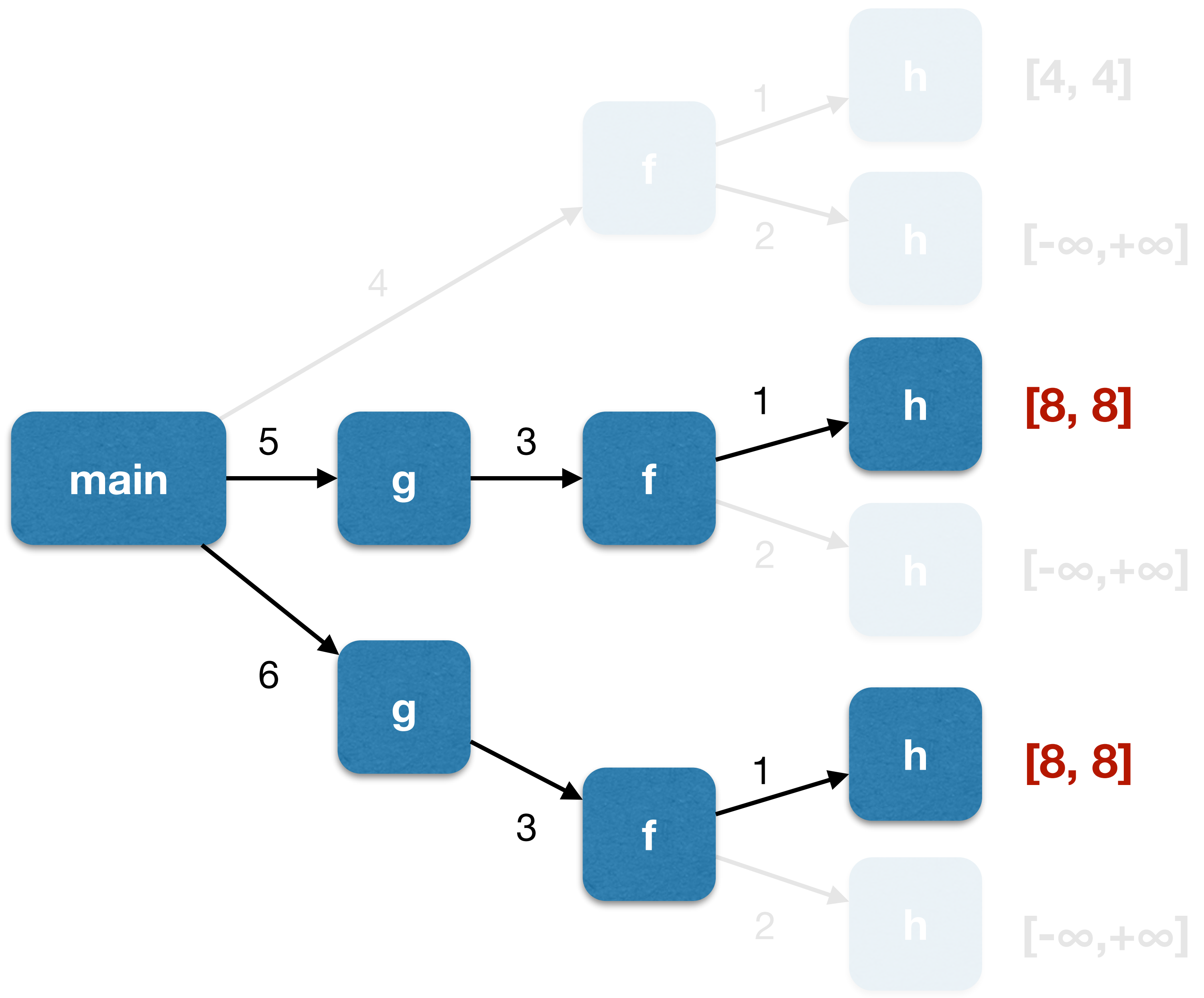
   }
```



Example: Context-Sensitivity

- Solution: **selective** context-sensitive analysis

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
     assert(q > 1); // Q2: not always true
   }

3: void g() { f(8); }

   void main(){
4:   f(4);
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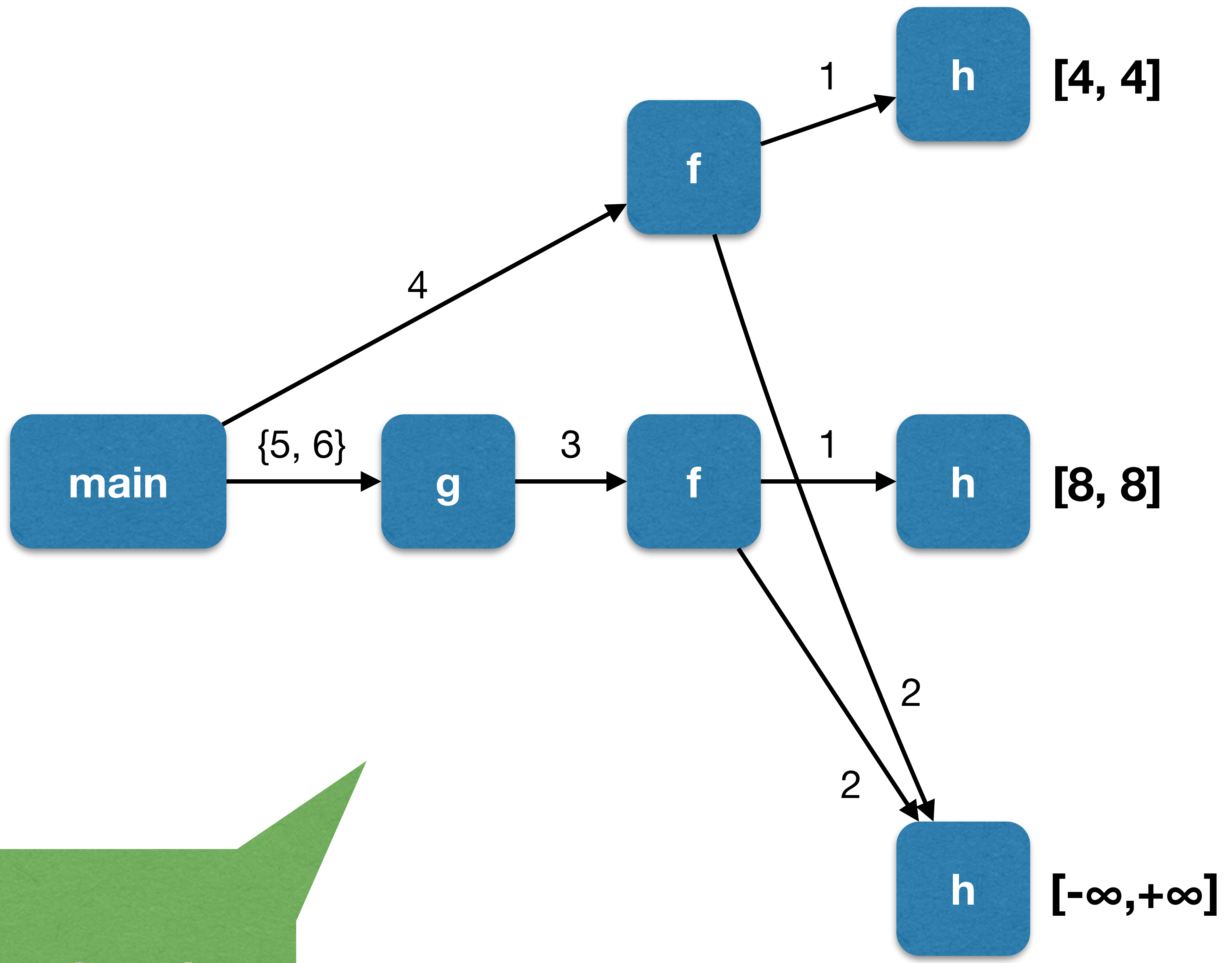
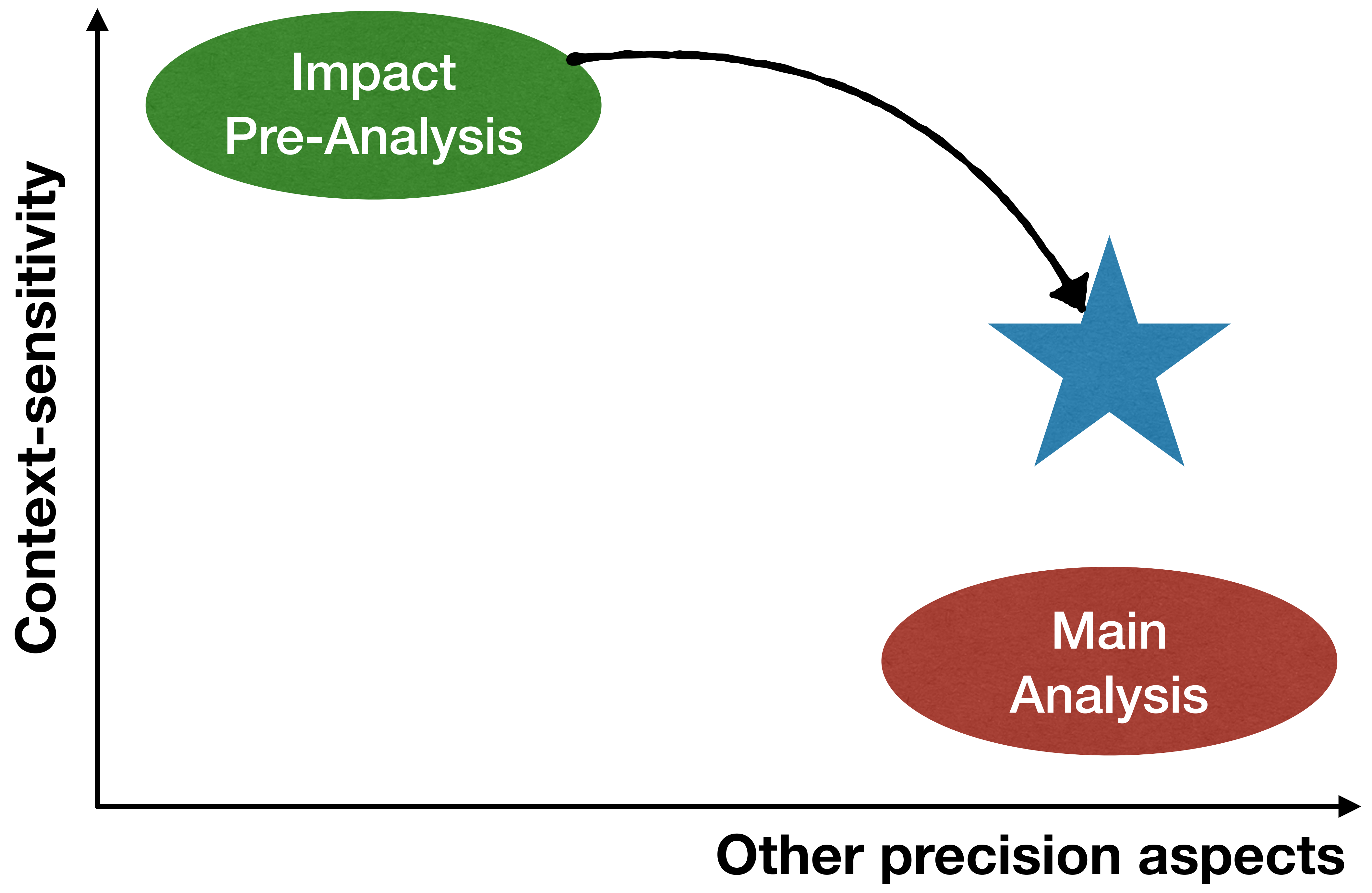
   }
```



Q: How to infer this selective context-sensitivity?

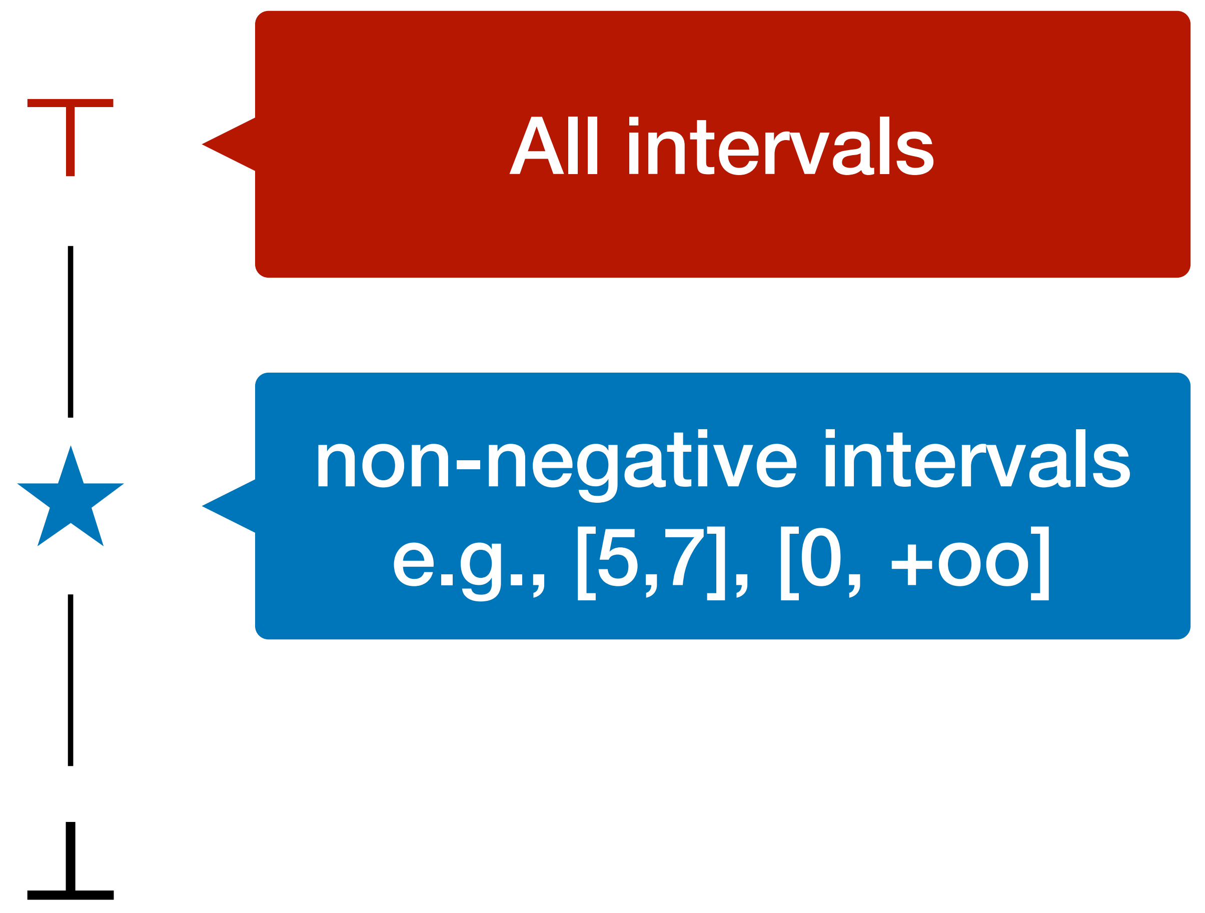
Key Idea: Impact Pre-Analysis

- Estimate the impact of X-sensitivity on main analysis
  - Fully X-sensitive, but approximated in other precision aspects



Design of Impact Pre-Analysis

- Main analysis: context-insensitive + interval domain
- Impact pre-analysis: fully context-sensitive + approximated interval domain



$$\wp(\mathbb{Z}^\sharp) \xleftrightarrow[\alpha]{\gamma} \{\bot, \star, \top\}$$

Running Impact Pre-Analysis

- Impact pre-analysis: fully context-sensitive + approximated interval domain

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
     assert(p > 1); // Q1: always true
2:   q = h(input());
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3: void g() { f(8); }

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4:   f(4);
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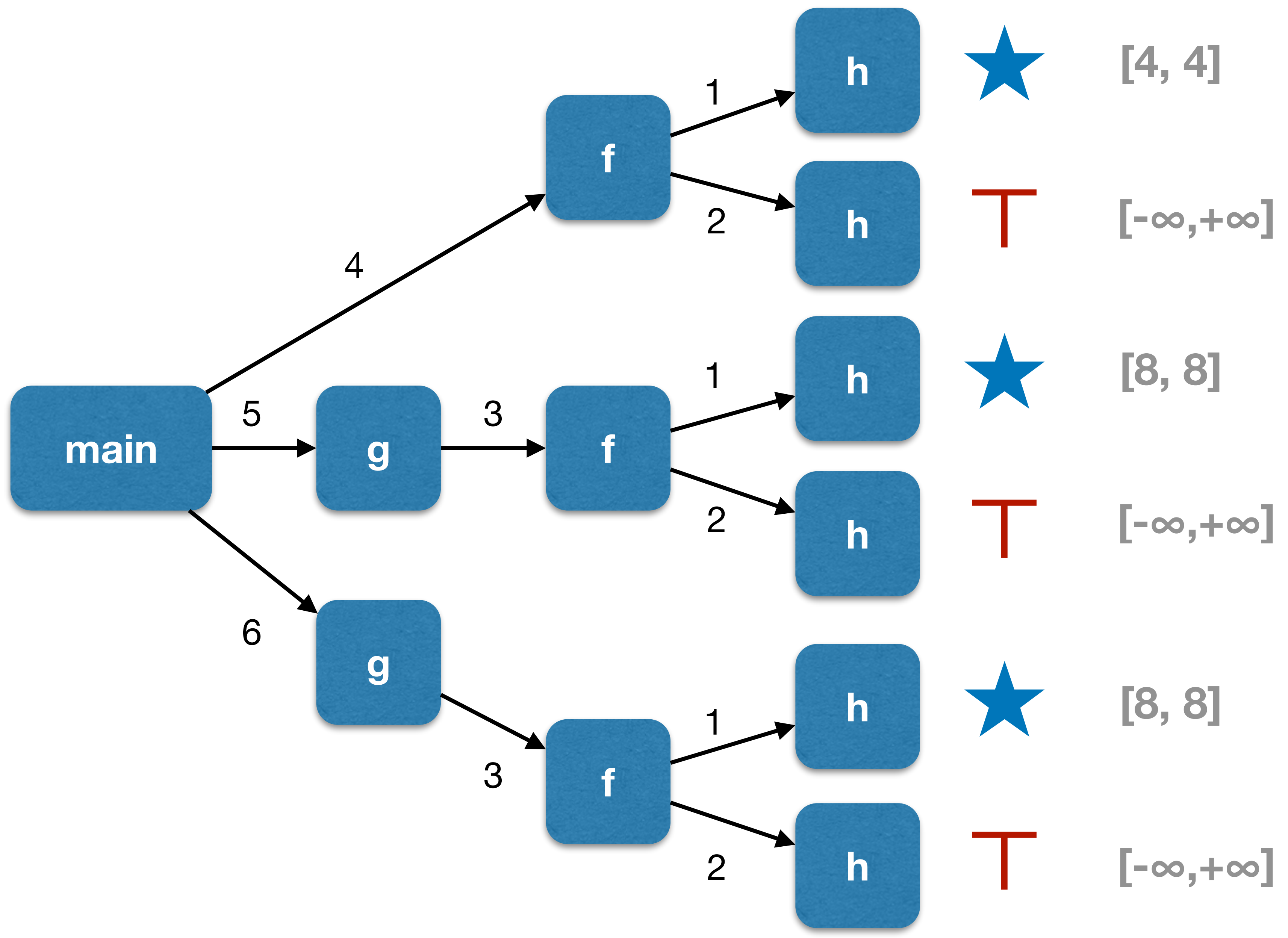

Constructing Selective Sensitivity

1. Collect queries whose expressions are assigned with ★

```
    int h(n) { return n; }

    void f(s) {
1:    p = h(s);
   ★  assert(p > 1); // Q1: always true
2:    q = h(input());
   ⊤  ~~assert(q > 1);~~ // Q2: not always true
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3: void g() { f(8); }

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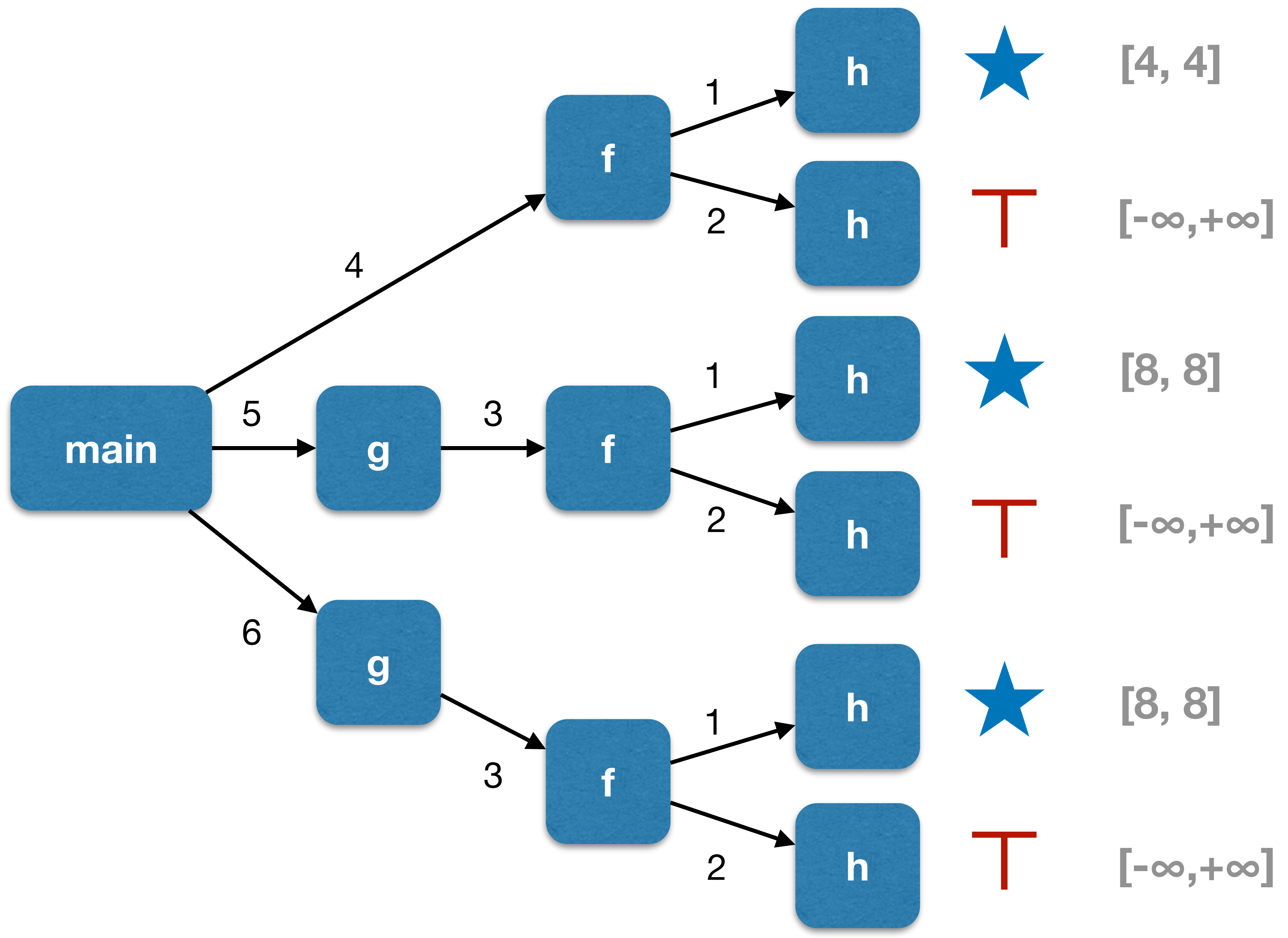

Constructing Selective Sensitivity

2. Find contexts that contribute to the selected queries

```
   int h(n) { return n; }

   void f(s) {
1:   p = h(s);
   ★ assert(p > 1); // Q1: always true
2:   q = h(input());
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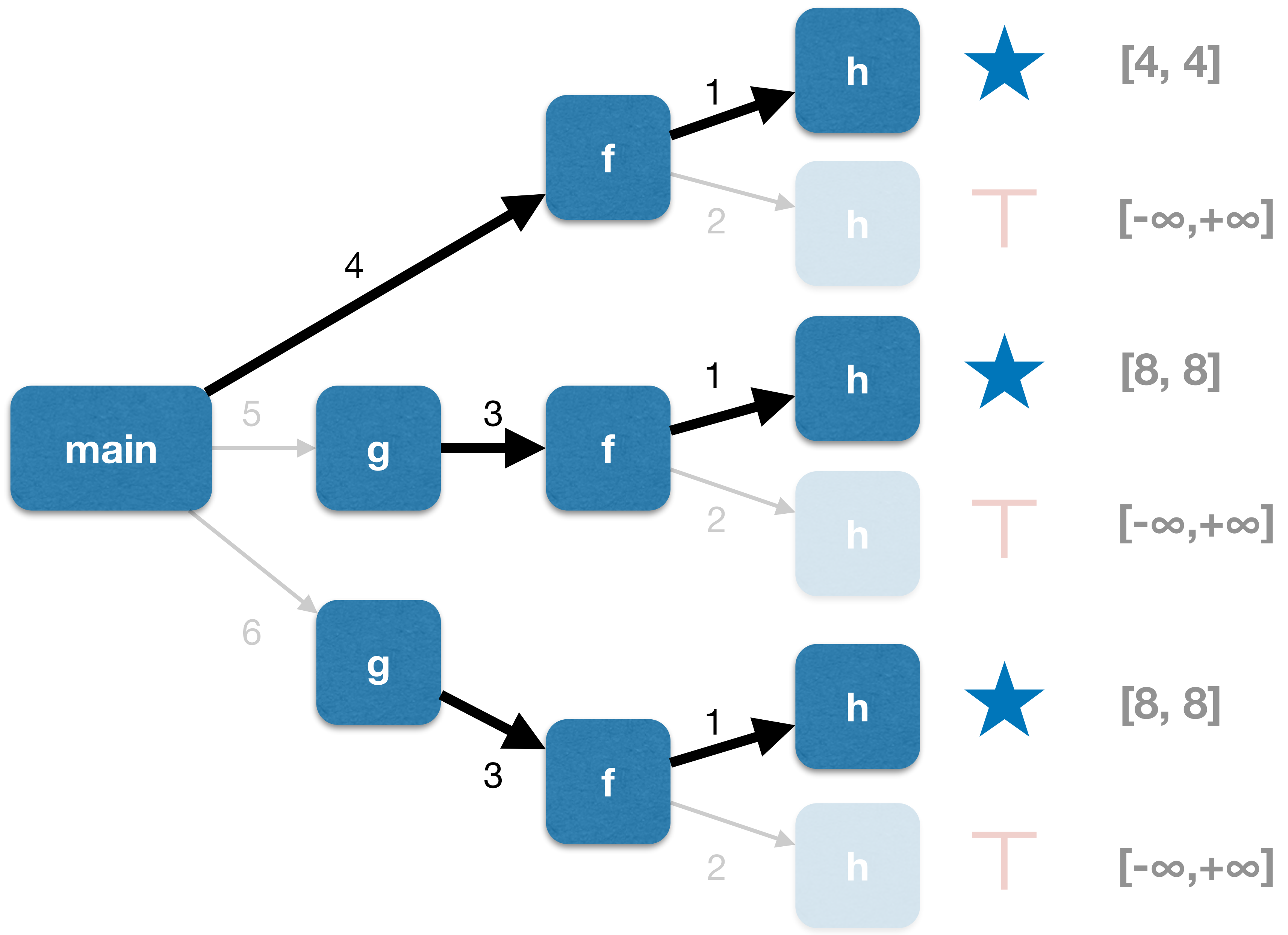


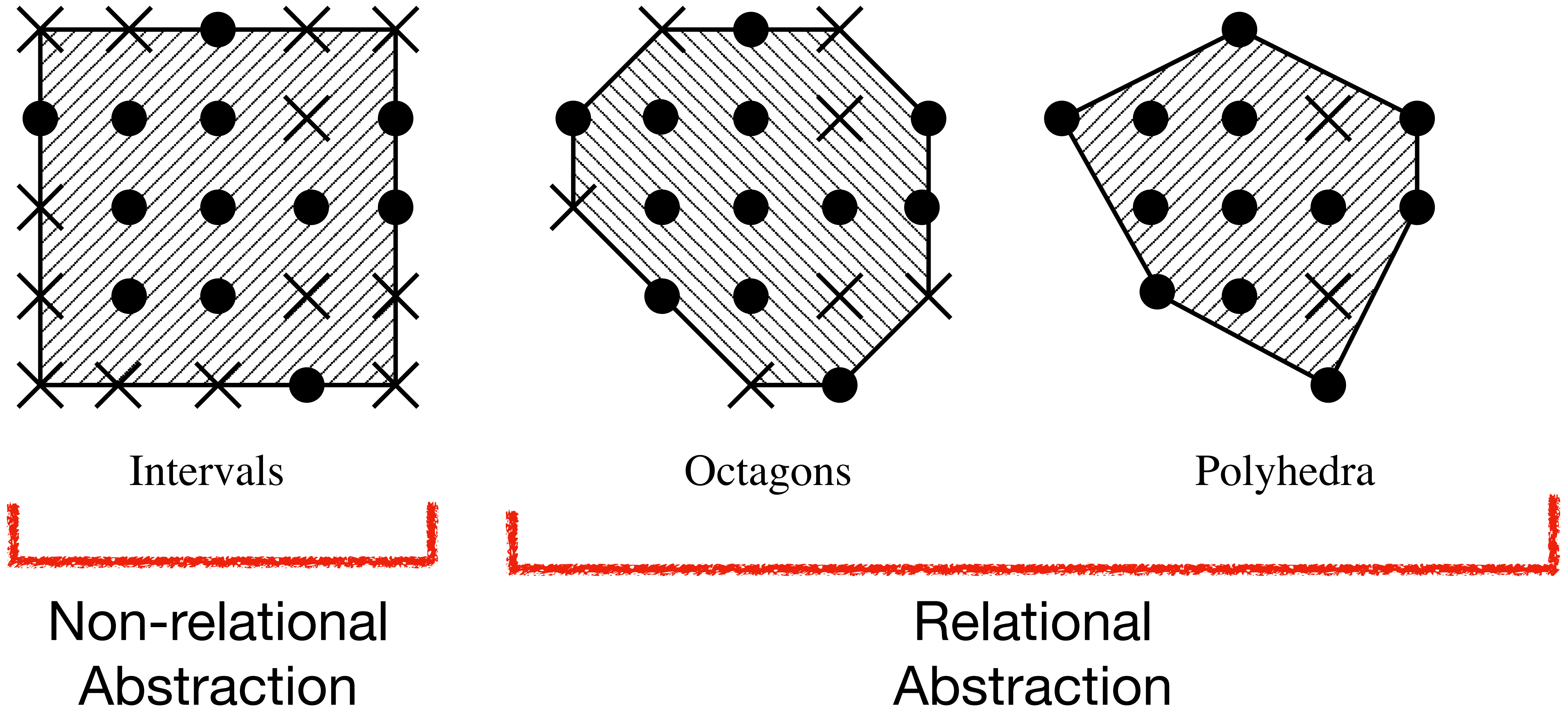
Selected contexts for function h: {4·1, 3·1}

Generality

- The same principle is applicable to other types of sensitivity
  - Running an impact pre-analysis
    (full X-sensitivity + aggressive abstraction of other aspects)
  - Select queries that are judged promising by the pre-analysis
  - Construct X-sensitivity that contributes to the selected queries

Example: Relational Analysis

- Keep track of relationships between variables in a certain form
  - E.g., octagon analysis: $(\pm x) - (\pm y) \leq c$



*A. Mine, The Octagon Abstract Domain, HOSC'06

Example: Relational Analysis

- Non-relational analysis with the interval domain

```
// b = [-oo, +oo]
1: int a = b;
2: int c = input();             // User input
3: for (i = 0; i < b; i++) {
4:   assert(i < a);             // Q1: always true
5:   assert(i < c);             // Q2: not always true
6: }
```

Var	Val
a	[-oo, +oo]
b	[-oo, +oo]
c	[-oo, +oo]
i	[0, +oo]

Example: Relational Analysis

- Fully relational analysis with the octagon domain: $(\pm x) - (\pm y) \leq c$

```
// b = [-oo, +oo]
int a = b;
int c = input();              // User input
for (i = 0; i < b; i++) {
  assert(i < a);              // Q1: always true
  assert(i < c);              // Q2: not always true
}
```

	a	b	c	i
a	0	∞	∞	∞
b	∞	0	∞	∞
c	∞	∞	0	∞
i	∞	∞	∞	0

{a, b, c, i}

*Consider x - y ≤ c only, for simplicity

Example: Relational Analysis

- Fully relational analysis with the octagon domain: $(\pm x) - (\pm y) \leq c$

```
// b = [-oo, +oo]
int a = b;
int c = input();            // User input
for (i = 0; i < b; i++) {
  assert(i < a);            // Q1: always true
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}
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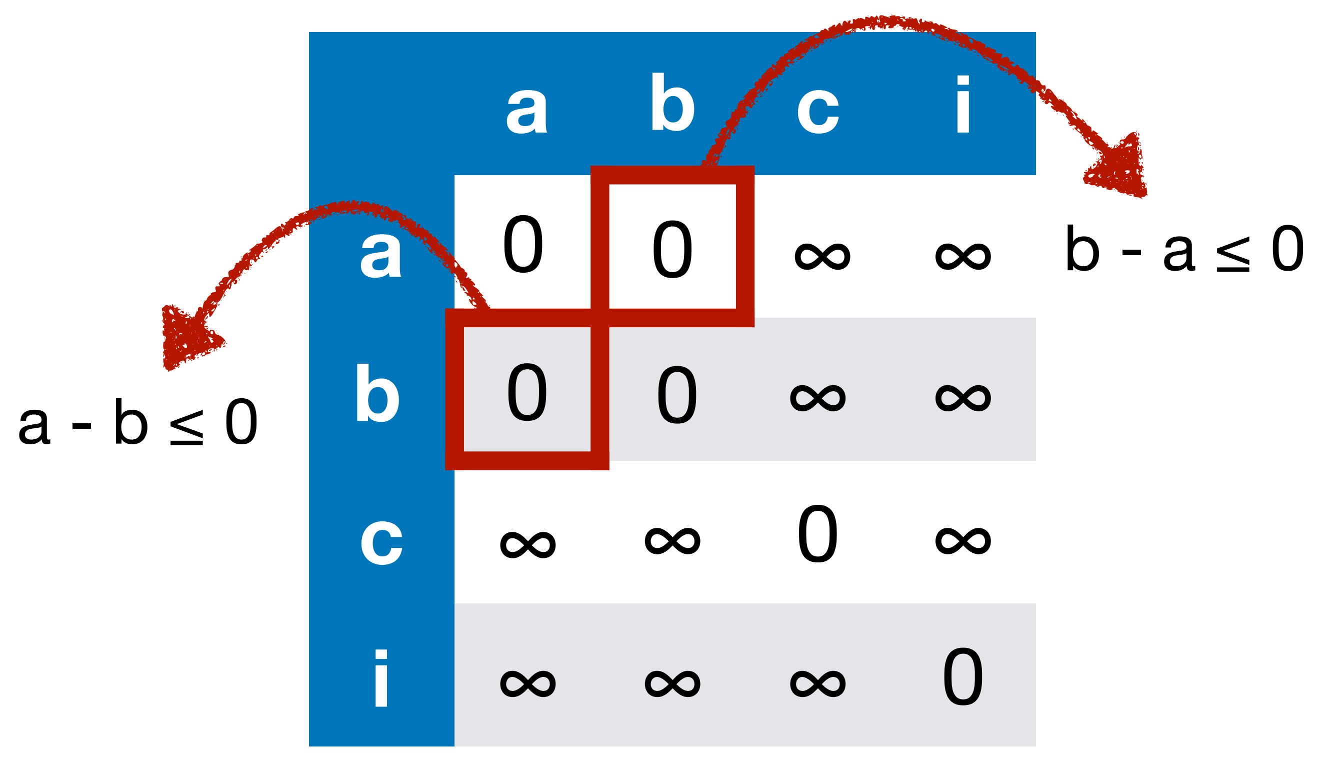

	a	b	c	i
a	0	0	∞	∞
b	0	0	∞	∞
c	∞	∞	0	∞
i	∞	∞	∞	0

{a, b, c, i}

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Example: Relational Analysis

- Fully relational analysis with the octagon domain: $(\pm x) - (\pm y) \leq c$

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}
```

	a	b	c	i
a	0	0	∞	∞
b	0	0	∞	∞
c	∞	∞	0	∞
i	∞	∞	∞	0

c - a ≤ ∞
c - b ≤ ∞

a - c ≤ ∞
b - c ≤ ∞

{a, b, c, i}

*Consider x - y ≤ c only, for simplicity

Example: Relational Analysis

- Fully relational analysis with the octagon domain: $(\pm x) - (\pm y) \leq c$

```
// b = [-oo, +oo]
int a = b;
int c = input();               // User input
for (i = 0; i < b; i++) {
  assert(i < a);               // Q1: always true
  assert(i < c);               // Q2: not always true
}
```

	a	b	c	i
a	0	0	∞	∞
b	0	0	∞	$\boxed{-1}$
c	∞	∞	0	∞
i	∞	∞	∞	0

i - b ≤ -1

{a, b, c, i}

*Consider x - y ≤ c only, for simplicity

Example: Relational Analysis

- Fully relational analysis with the octagon domain: $(\pm x) - (\pm y) \le c$

```
// b = [-oo, +oo]
int a = b;
int c = input();            // User input
for (i = 0; i < b; i++) {
  assert(i < a);            // Q1: always true
  assert(i < c);            // Q2: not always true
}
```

	a	b	c	i
a	0	$\boxed{0}$	∞	$\boxed{-1}$
b	0	0	∞	$\boxed{-1}$
c	∞	∞	0	∞
i	∞	∞	∞	0

$$\begin{aligned} & b - a \le 0 \\ \wedge\ & i - b \le -1 \\ \Rightarrow\ & i - a \le -1 \end{aligned}$$

{a, b, c, i}

*Consider x - y ≤ c only, for simplicity

Example: Relational Analysis

- Problem of fully relational analysis: **useless** relationship

```
// b = [-oo, +oo]
int a = b;
int c = input();            // User input
for (i = 0; i < b; i++) {
  assert(i < a);            // Q1: always true
  assert(i < c);            // Q2: not always true
}
```

	a	b	~~c~~	i
a	0	0	~~∞~~	-1
b	0	0	~~∞~~	-1
~~c~~	~~∞~~	~~∞~~	~~0~~	~~∞~~
i	∞	∞	~~∞~~	0

{a, b, ~~c~~, i}

*Consider x - y ≤ c only, for simplicity

Example: Relational Analysis

- Solution: **selective** relational analysis

```
// b = [-oo, +oo]
int a = b;
int c = input();             // User input
for (i = 0; i < b; i++) {
  assert(i < a);             // Q1: always true
  assert(i < c);             // Q2: not always true
}
```

	a	b	i
a	0	0	-1
b	0	0	-1
i	∞	∞	0

{a, b, i}

+

Var	Val
c	[-oo, +oo]

{c}

*Consider x - y ≤ c only, for simplicity

Design of Impact Pre-Analysis

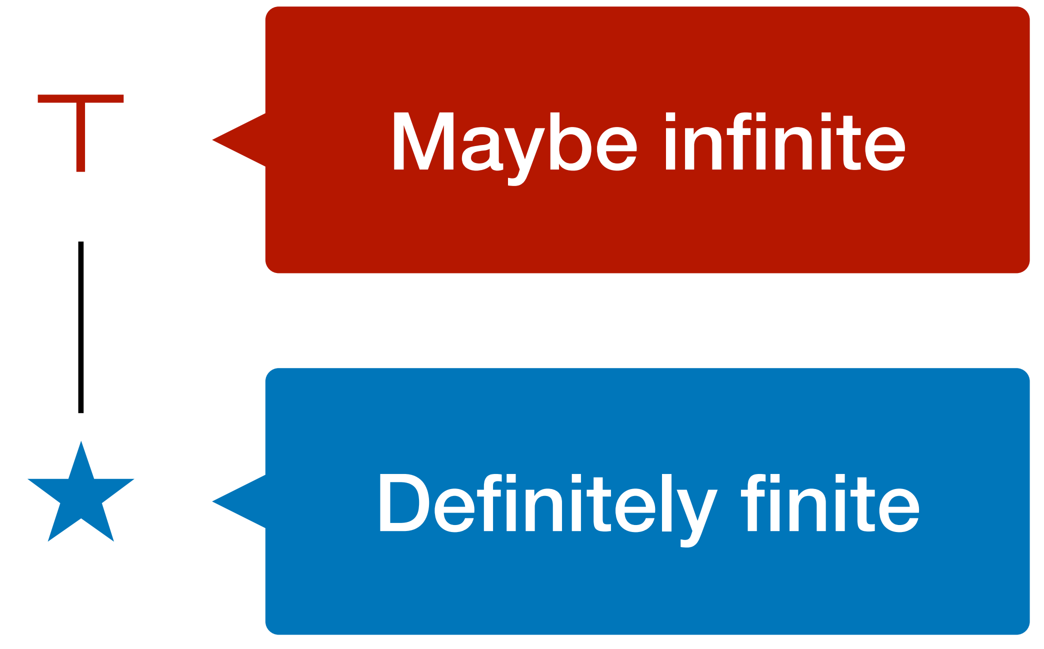
- Main analysis: non-relational analysis
- Impact pre-analysis: fully relational analysis + approximated upper bound

	a	b	c	i
a	0	0	∞	-1
b	0	0	∞	-1
c	∞	∞	0	∞
i	∞	∞	∞	0

Fully relational octagon analysis

	a	b	c	i
a	★	★	⊤	★
b	★	★	⊤	★
c	⊤	⊤	★	⊤
i	⊤	⊤	⊤	★

Fully relational impact pre-analysis



Constructing Selective Sensitivity

1. Collect queries whose expressions are assigned with ★

```
// b = [-oo, +oo]
int a = b;
int c = input();             // User input
for (i = 0; i < b; i++) {
  assert(i < a); ★           // Q1: always true
  ~~assert(i < c);~~ ⊤           // Q2: not always true
}
```

	a	b	c	i
a	★	★	⊤	★
b	★	★	⊤	★
c	⊤	⊤	★	⊤
i	⊤	⊤	⊤	★

Constructing Selective Sensitivity

2. Find variable relationships that contribute to the selected queries

```
// b = [-oo, +oo]
int a = b;
int c = input();          // User input
for (i = 0; i < b; i++) {
  assert(i < a); ★        // Q1: always true
  ~~assert(i < c);~~ ⊤        // Q2: not always true
}
```

	a	b	c	i
a	★	★	⊤	★
b	★	★	⊤	★
c	⊤	⊤	★	⊤
i	⊤	⊤	⊤	★

Selected variables: {a, b, i}

Summary

- Selective X-sensitivity: a framework for balancing between **cost & accuracy**
- Key idea: **"Apply X-sensitivity only when it matters"**
- Estimate the impact of X using the **impact pre-analysis**
  - Full X-sensitivity + aggressive approximation of other precision aspects
- Construct selective X-sensitivity from the guidance of the impact estimation