Static Analysis: Overview, Syntactic Analysis and Abstract Interpretation

TDDC90: Software Security

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Outline

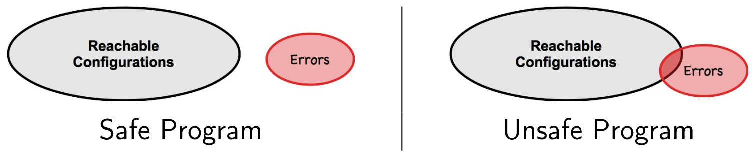
Static Program Analysis

Static Program Analysis analyses computer programs **statically**, i.e., without executing them (as opposed to *dynamic analysis* that does execute the programs wrt. some specific input):

- No need to run programs, before deployment
- No need to restrict to a single input as for testing
- Useful in compiler optimization, program analysis, finding security vulnerabilities and verification
- Often performed on source code, sometimes on object code
- Usually highly automated though with the possibility of some user interaction
- From scalable bug hunting tools without guarantees to heavy weight verification frameworks for safety critical systems

Static Program Analysis and Approximations

We want to answer whether the program is **safe** or not (i.e., has some erroneous reachable configurations or not):

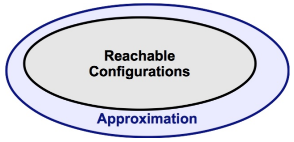


Static Program Analysis and Approximations

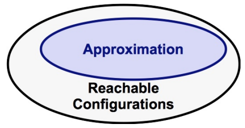
- Finding all configurations or behaviours (and hence errors) of arbitrary computer programs can be easily reduced to the halting problem of a Turing machine.
- This problem is proven to be undecidable, i.e., there is no algorithm that is guaranteed to terminate and to give an exact answer to the problem.
- An algorithm is **sound** in the case where each time it reports the program is safe wrt. some errors, then the original program is indeed safe wrt. those errors
- An algorithm is **complete** in the case where each time it is given a program that is safe wrt. some errors, then it does report it to be safe wrt. those errors

Static Program Analysis and Approximations

- The idea is then to come up with efficient approximations and algorithms to give correct answers in as many cases as possible.



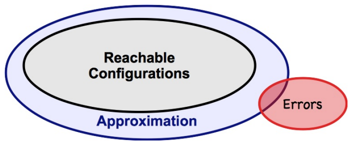
Over-approximation



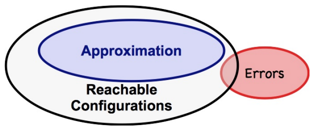
Under-approximation

Static Program Analysis and Approximations

- A sound analysis cannot give **false negatives**
- A complete analysis cannot give **false positives**



False Positive



False Negative

These Two Lectures

These two lectures on static program analysis will briefly introduce different types of analysis:

- This lecture:
  - syntactic analysis: scalable but neither sound nor complete
  - data flow analysis and abstract interpretation sound but not complete
- Next lecture:
  - symbolic executions: complete but not sound
  - inductive methods: may require heavy human interaction in proving the program correct

Administrative Aspects:

- There will be two lab sessions
- These might not be enough and you might have to work more
- You will need to write down your answers to each question on a draft.
- you will need to demonstrate (individually) your answers in one of the lab sessions on a computer for me (for group A) or Ulf (group B).
- Once you get the green light, you can write your report in a pdf form and send it (in pairs) to me or Ulf.
- You will get questions in the final exam about these two lectures.

Outline

Overview

Syntactic Analysis

Abstract Interpretation

Automatic Unsound and Incomplete Analysis

- Tools such as the open source *Splint* or the commercial *Clockworck* and *Coverity* trade guarantees for scalability
- Not all reported errors are actual errors (false positives) and even if the program reports no errors there might still be uncovered errors (false negatives)
- A user needs therefore to carefully check each reported error, and to be aware that there might be more uncovered errors

Unsound and Incomplete analysis: Splint

- Some tools are augmented versions of grep and look for occurrences of memcpy, pointer dereferences ...
- The open source Splint tool checks C code for security vulnerabilities and programming errors.
- Splint does parse the source code and looks for certain patterns such as:
  - unused method parameters
  - loop tests that are not modified by the loop,
  - variables used before definitions,
  - null pointer dereference
  - over writing allocated structures
  - and many more ...

Unsound and Incomplete analysis: Splint

Pointer dereference

```
...
 return *s; // warning about dereference of possibly null pointer s
...
if(s!=NULL)
  return *s; //does not give warnings because s was checked
```

Undefined variables:

```
extern int val  (int *x);

int dumbfunc (int *x, int i)
{
  if (i > 0) return *x; //Value *x used before definition
  else return val (x); //Passed storage x not completely defined
}
```

Unsound and Incomplete analysis: Splint

- Still, the number of false positives remains very important, which may diminish the attention of the user since splint looks for "dangerous" patterns
- An important number of flags can be used to enable, inhibit or organize the kind of errors Splint should look for
- Splint gives the possibility to the user to annotate the source code in order to eliminate warnings
- Real errors can be made quite with annotations. In fact real errors will remain unnoticed with or without annotations

Outline

Abstract Interpretation

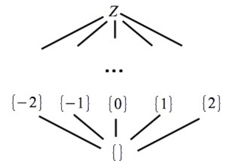
- Suppose you have a program analysis that captures the program behavior but that is inefficient or uncomputable (e.g. enumerating all possible values at each program location)
- You want an analysis that is efficient but that can also over-approximate all behaviors of the program (e.g. tracking only key properties of the values)

The sign example

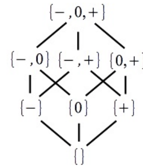
- Consider a language where you can multiply ($\times$), sum ($+$) and substract ($-$) integer variables.
- If you are only interested in the signs of the variables values, then you can associate, at each position of the program, a subset of $\{+, 0, -\}$, instead of a subset of $\mathbb{Z}$, to each variable
- For an integer variable, the set of concrete values at a location is in $\mathcal{P}(\mathbb{Z})$. Concrete sets are ordered with the subset relation $\sqsubseteq_c$ on $\mathcal{P}(\mathbb{Z})$. We can associate $\mathbb{Z}$ to each variable in each location, but that is not precise. We write $S_1 \sqsubseteq_c S_2$ to mean that S_1 is more precise than S_2.
- We approximate concrete values with an element in $\mathcal{P}(\{-, 0, +\})$. For instance, $\{0, +\}$ means the variable is larger or equal than zero. For A_1, A_2 in $\mathcal{P}(\{-, 0, +\})$, we write $A_1 \sqsubseteq_a A_2$ to mean that A_1 is more precise than A_2.

The sign example: concrete and abstract lattices

- A pair $(Q, \preceq)$ is a lattice if each pair p, q in Q has
  - a greatest lower bound $p \sqcap q$ wrt. $\preceq$ (aka meet), and
  - a least upper bound $p \sqcup q$ wrt. $\preceq$ (aka join)
- $(\mathcal{P}(\mathbb{Z}), \sqsubseteq_c)$ and $(\mathcal{P}(\{-, 0, +\}), \sqsubseteq_a)$ are lattices



Concrete lattice
$(\mathcal{P}(\mathbb{Z}), \sqsubseteq_c)$

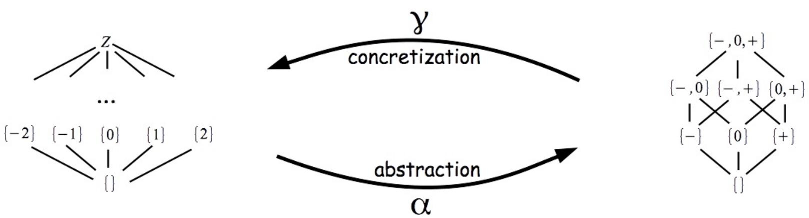


Abstract lattice
$(\mathcal{P}(\{-, 0, +\}), \sqsubseteq_a)$

- For any $S \in \mathcal{P}(\mathbb{Z})$, $\{\} \sqsubseteq_c S$
- If $A_1 = \{-, 0\}$ and $A_2 = \{0, +\}$, then $A_1 \sqcap_a A_2 = \{0\}$ and $A_1 \sqcup_a A_2 = \{-, 0, +\}$

The sign example: Galois connections

- (α, γ) is a Galois connection if, for all $S \in \mathcal{P}(\mathbb{Z})$ and $A \in \mathcal{P}(\{-, 0, +\})$, $\alpha(S) \sqsubseteq_a A$ iff $S \sqsubseteq_b \gamma(A)$
- E.g. here, $\alpha(S) = \{+\}$ if $S \subseteq \{i | i > 0\}$ and $\gamma(A) = \{i | i \leq 0\}$ if A is $\{-, 0\}$
- Interestingly: $S \sqsubseteq_c \gamma \circ \alpha(S)$ and $\alpha \circ \gamma(A) \sqsubseteq_a A$ for any concrete and abstract elements S, A.



Concrete lattice — A Galois connection — Abstract lattice

The sign example: abstract transformers

Let A, B be two abstract elements.

$\otimes$	-	0	+
-	{+}	{0}	{-}
0	{0}	{0}	{0}
+	{-}	{0}	{+}

$$A \otimes B = \bigcup_{a \in A, b \in B} a \otimes b$$

$\oplus$	-	0	+
-	{-}	{-}	{-,0,+}
0	{-}	{0}	{+}
+	{-,0,+}	{+}	{+}

$$A \oplus B = \bigcup_{a \in A, b \in B} a \oplus b$$

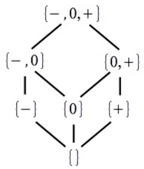
	-	0	+
$\underline{++}$	{-,0}	{+}	{+}

$$A\underline{++} = \cup_{a \in A} a\underline{++}$$

	-	0	+
$\underline{--}$	{-}	{-}	{0,+}

$$A\underline{--} = \cup_{a \in A} a\underline{--}$$

Example 1

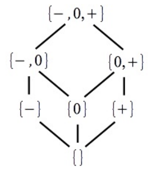



```
while(x>0){

  if(x>0){

    x--;

  }else{

    x++;

  }

  assert(x>=0);

}
.
```

```
// x: {-,0,+}
while(x > 0){
// x:  {}
  if(x > 0){
// x: {}
    x--;
// x: {}
  }else{
// x: {}
    x++;
// x:{}
  }
// x: {}
  assert(x >= 0);
// x: {}
}
// x: {}
```

```
// x: {-,0,+}
while(x > 0){
// x:  {+}
  if(x > 0){
// x: {+}
    x--;
// x: {0,+}
  }else{
// x: {}
    x++;
// x: {}
  }
// x: {0,+}
  assert(x >= 0);
// x: {0,+}
}
// x: {-,0}
```

Example 2

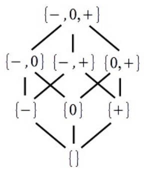



```
while(x!=0){

  assert(x!=0);

  if(x>0){

    x,y=x--,1;

  }else{

    x,y=x++,-1;

  }

  assert(y!=0);

}
.
```

```
// x: {-,0,+}; y: {-,0,+}
while(x != 0){
// x:  {-,0,+}; y: {-,0,+}
  assert(x!=0);
// x: {-,0,+}; y: {-,0,+}
  if(x > 0){
// x: {+}; y: {-,0,+}
    x,y=x--,1;
// x: {}; y: {}
  }else{
// x: {0,+}; y: {-,0,+}
    x,y=x++,-1;
// x:{}; y: {}
  }
// x: {}; y: {}
  assert(y!=0);
// x: {}; y: {}
}
// x: {0}; y: {-,0,+}
```

```
// x: {-,0,+}; y: {-,0,+}
while(x != 0){
// x:  {-,0,+}; y: {-,0,+}
  assert(x!=0);
// x: {-,0,+}; y: {-,0,+}
  if(x > 0){
// x: {+}; y: {-,0,+}
    x,y=x--,1;
// x: {0,+}; y: {+}
  }else{
// x: {-,0}; y: {-,0,+}
    x,y=x++,-1;
// x:{-,0,+}; y: {-}
  }
// x: {-,0,+}; y: {-,0,+}
  assert(y!=0);
// x: {-,0,+}; y: {-,0,+}
}
// x: {0}; y: {-,0,+}
```

Example 3: more precise abstract domain

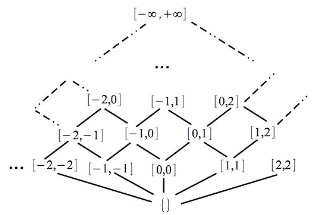



```
while(x!=0){

  assert(x!=0);

  if(x>0){

    x,y=x--,1;

  }else{

    x,y=x++,-1;

  }

  assert(y!=0);

}
.
```

```
// x: {-,0,+}; y: {-,0,+}
while(x != 0){
// x:  {-,+}; y: {-,0,+}
  assert(x!=0);
// x: {-,+}; y: {-,0,+}
  if(x > 0){
// x: {+}; y: {-,0,+}
    x,y=x--,1;
// x: {}; y: {}
  }else{
// x: {+}; y: {-,0,+}
    x,y=x++,-1;
// x:{}; y: {}
  }
// x: {}; y: {}
  assert(y!=0);
// x: {}; y: {}
}
// x: {0}; y: {-,0,+}
```

```
// x: {-,0,+}; y: {-,0,+}
while(x != 0){
// x:  {-,+}; y: {-,0,+}
  assert(x!=0);
// x: {-,+}; y: {-,0,+}
  if(x > 0){
// x: {+}; y: {-,0,+}
    x,y=x--,1;
// x: {0,+}; y: {+}
  }else{
// x: {-}; y: {-,0,+}
    x,y=x++,-1;
// x:{-,0}; y: {-}
  }
// x: {-,0,+}; y: {-,+}
  assert(y!=0);
// x: {-,0,+}; y: {-,+}
}
// x: {0}; y: {-,0,+}
```

Example 4: interval domain



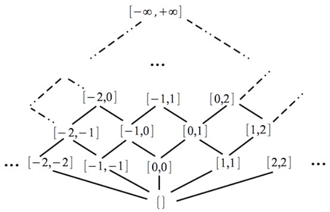
$[a,b] \sqsubseteq [c,d]$ iff $c \leq a$ and $b \leq d$
$[a,b] \sqcup [c,d]$ is $[inf\{a,c\}, sup\{b,d\}]$
$[a,b] \sqcap [c,d]$ is $[sup\{a,c\}, inf\{b,d\}]$

```
x,y=0,0;

while(x!=100){

    x,y=x++,y++;

}

assert(x==100);

assert(y==100);
.
```

```
// x:[-oo,+oo], y:[-oo,+oo]
x,y=0,0;
// x:[0,0], y:[0,0]
while(x!=100){
    // x:[0,0], y:[0,0]
    x,y=x++,y++;
    // x:[0,1], y:[0,1]
}
// x:[], y:[]
assert(x==100);
// x:[], y:[]
assert(y==100);
// x:[], y:[]
```

```
// x:[-oo,+oo], y:[-oo,+oo]
x,y=0,0;
// x:[0,0], y:[0,0]
while(x!=100){
    // x:[0,1], y:[0,1]
    x,y=x++,y++;
    // x:[0,2], y:[0,2]
}
// x:[], y:[]
assert(x==100);
// x:[], y:[]
assert(y==100);
// x:[], y:[]
```

Example 4: interval domain, widening



$[0,0],[0,1],[0,2],[0,3]\ldots.$
would take 100 steps to converge.
Sometimes too many steps.
For this use some widening operator ∇.
Intuitively, an acceleration that ensures termination

```
x,y=0,0;

while(x!=100){

    x,y=x++,y++;

}

assert(x==100);

assert(y==100);
.
```

```
// x:[-oo,+oo], y:[-oo,+oo]
x,y=0,0;
// x:[0,0], y:[0,0]
while(x!=100){
    // x:[0,99], y:[0,+oo]
    x,y=x++,y++;
    // x:[0,100], y:[0,+oo]
}
// x:[], y:[]
assert(x==100);
// x:[], y:[]
assert(y==100);
// x:[], y:[]
```

```
// x:[-oo,+oo], y:[-oo,+oo]
x,y=0,0;
// x:[0,0], y:[0,0]
while(x!=100){
    // x:[0,99], y:[0,+oo]
    x,y=x++,y++;
    // x:[0,100], y:[0,+oo]
}
// x:[100,100], y:[0,+oo]
assert(x==100);
// x:[100,100], y:[0,+oo]
assert(y==100);
// x:[100,100], y:[0,+oo]
```

You can play with more numerical domains at this web interface
`http://pop-art.inrialpes.fr/interproc/interprocweb.cgi`