Crystal-izing Sophisticated Code Analyses

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http://code.google.com/p/crystalsaf

Installation

- Pre-requisites
  - Eclipse with
    - Java Development Tools (JDT)
    - Plugin Development Environment (PDE)
  - Crystal
    - Available from our Eclipse update site
    - http://crystalsaf.googlecode.com/svn/trunk/EclipseUpdate/

Crystal

- A framework for creating static analyses
  - AST walkers
  - Simple dataflow
  - Branch-sensitive dataflow
  - Use of specifications
- Primarily for educational purposes
  - Easy startup into a static analysis
  - Direct from theory to implementation
  - Incremental development of analyses
  - "Wow factor": power of Eclipse
- Also found to be useful for research prototypes

Crystal in the classroom

- Crystal is used in CMU graduate analysis courses
  - Courses: Analysis of Software Artifacts, Program Analysis
  - Students: Ph.D. students, professional masters' students
- Students will learn
  - What can affect the usability and precision of a static analysis
  - What kind of problems static analysis can solve

Crystal in research

- High transferability from paper to code made Crystal natural choice for research
- Currently 4 research analyses written in Crystal
  - 3 are published (OOPSLA 08, ECOOP 09, OOPSLA 09)
- Allows incremental development to more sophisticated features
  - Annotations with custom parsers
  - Branch-sensitivity
  - Automated testing
  - Widening v. regular join

Demonstration

- Install Crystal
- Create an Eclipse Plugin
- Create an Analysis class
- Register the analysis
- Run the analysis
- Create a visitor
- Run the analysis again

Register and Run

- Create a new plugin project
  - Make it depend on Crystal and JDT
- Implement ICrystalAnalysis
- Register with the extension-point CrystalAnalysis in the plugin.xml file

- Select Run -> Run Configuration…
- Make a new Eclipse configuration
- Run! Your analysis name should appear in the Crystal menu.

Steps for making an analysis

- Install Crystal
- Register an analysis
- **Create a simple AST walker for nullness**
- Add a simple flow analysis
- Add annotations
- Add branch-sensitivity

Use an AST walker

- We're ready to make an analysis now.
- **What kinds of expressions do we want to check for an null pointer analysis?**
  - Method calls
  - Field access
  - Array access
- **In analyzeMethod(), create an ASTVisitor that gives an error when it encounters these operations.**

Everything running?

- Create a new project in the child Eclipse
- Add code to analyze
- Test with Crystal->MyAnalysis

- Can also run automated tests in JUnit
  - Will not cover that today
  - See wiki for more information

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Abstract interpretation concepts

- Lattice
  - The abstract states the program can be in
- Control flow graph
  - The order of control flow through the nodes of the AST
- Transfer functions
  - How the states change as the analysis encounters new program instructions
- Worklist algorithm
  - Traverses the control flow graph and runs the transfer functions

Abstract interpretation concepts

- Lattice
  - A finite lattice of the abstract states the program can be in
- Control flow graph
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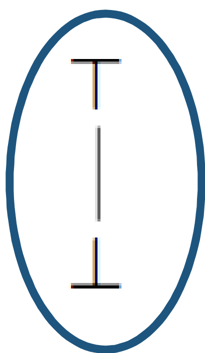
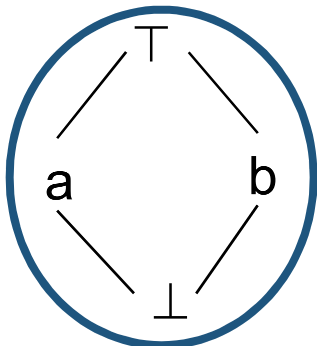
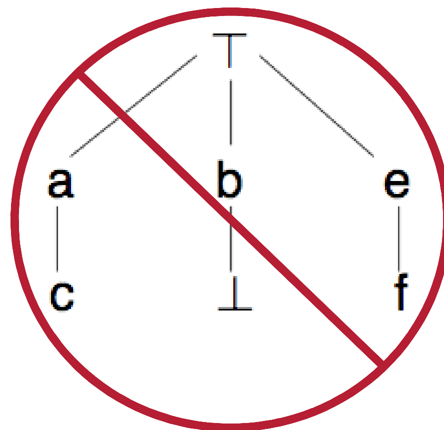
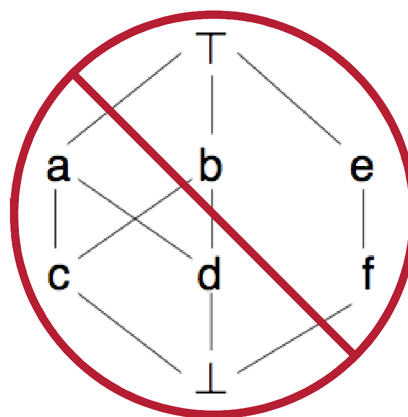
Lattice review

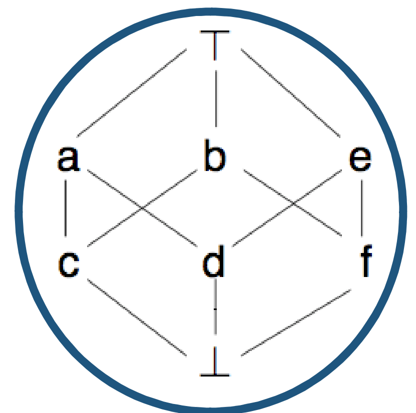
- Top of lattice represents least precise info
- Bottom of lattice represents an unanalyzed element
- Must have finite height to ensure termination
- Unique least upper bound must exist for any two elements







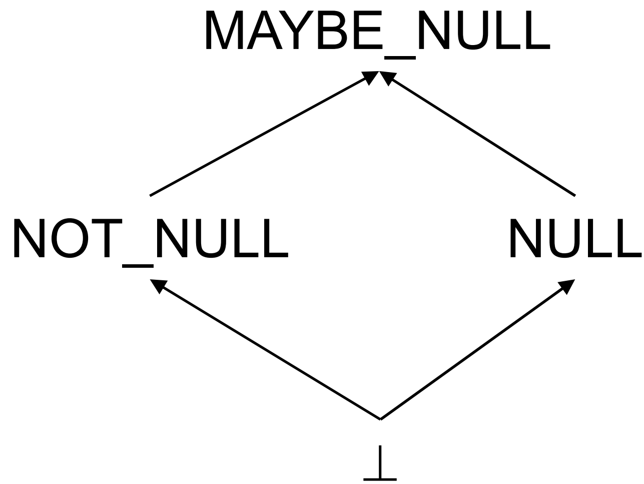




Transfer function review

- Given
  - An instruction
  - An incoming lattice element σ
- Produce
  - An outgoing lattice element σ'
- $f(\text{instr}, \sigma) = \sigma'$
- Make a different transfer function on each type of instruction

A simple null analysis



- Map all variables to an element in the lattice above
- Tuple Lattice: A lattice which maps a key to an element in another lattice

σ is a map of every program variable to a null lattice element

- *f*(x = null, σ) =
  σ[x→NULL]
- *f*(x = y, σ) =
  σ[x→σ(y)]
- *f*(x = new C(), σ) =
  σ[x→NOT_NULL]
- *f*(x = y.m(z1,…,zn), σ) =
  σ[y→NOT_NULL]
- (array access, field access, etc.)

The lattice

- **What are the elements in the lattice?**
  - Bottom, null, not null, and maybe null
- **Create a type which represents the elements**
  - Crystal allows this to be an arbitrary type
  - This is likely an immutable type, like an enum

```
public enum NullLatticeElement {
  BOTTOM, NULL, NOT_NULL, MAYBE_NULL;
}
```

- Tuple Lattices
  - We will use TupleLatticeElement
  - Just create the type which represents the sub-lattice

The lattice

- **What is the bottom-most element?**
- **What is the the top-most?**
- **What is the ordering of elements?**
- **What does the join operation look like?**

- **Extend SimpleLatticeOperations<LE>**
  - LE bottom()
  - boolean atLeastAsPrecise(LE, LE)
  - LE join(LE, LE)
  - LE copy(LE)

Setting up the flow analysis

- **What is the lattice element at the start of the method?**
  - Everything may be null (except **this** is not null)
- **Extend AbstractingTransferFunction**
  - Implement createEntryValue() and getLatticeOperations()
  - (Don't override the transfer functions yet)
- We'll also now have the visitor call the flow analysis

Transfer functions

- **Which instructions cause the lattice element to change? How do they change the lattice element?**
  - Null: makes target null
  - Constructor: makes target non-null
  - Copying assignment: makes target same as right side
- **In the derived transfer function, override the relevant instructions**

You now have a Crystal flow analysis

- **And that's it!**
- From here, we're just going to improve it
  - Annotations: teach students power of specifications
  - Branch-sensitivity: teach students power of abstractions closer to code
- We'll move a little faster
- Assistants are ready to help if you wish to follow along

Why Three Address Code

- Does mean students work with both Eclipse AST and TAC
- However
  - TAC has no sub-expressions
  - TAC has many fewer kinds of nodes
- Students able to understand TAC as it matched what they wrote down on paper

Relevant packages

- **edu.cmu.cs.crystal**
  - Core package for analyses
- **org.eclipse.jdt.core.dom**
  - The Eclipse AST
- **edu.cmu.cs.crystal.simple**
  - Simple interfaces for flow analyses
- **edu.cmu.cs.crystal.tac.model**
  - The interfaces for three address code instructions

Steps for making an analysis

- Install Crystal
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- **Add annotations**
- Add branch-sensitivity

Annotations

- **What specifications could we add to make the analysis more precise?**
  - Non-null on method parameters

- **Create a Java annotation**
  - Put it in a jar separate from your analysis
  - Make it available to the code being analyzed

```java
@Target({ElementType.METHOD, ElementType.PARAMETER})
public @interface NonNull {}
```

Annotations

- **What transfer functions can use this annotation to improve precision?**
  - Initial lattice information
  - Method call instruction (return value)
- Annotations are available from the Eclipse AST
  - But hard to get
  - No desugaring
- **Use the AnnotationDatabase**
  - Pass in an AnnotationDatabase to the transfer functions
  - Query it to find instances of the @NotNull annotation
- Can also give Crystal a custom parser for complex annotations
  - @Invariant(“x == foo and y != bar”)

Annotations

- **Where can the visitor use annotations for additional checking?**
  - Method call parameters and return value
  - Constructor call parameters

- **Use the AnnotationDatabase**
  - Query it to find instances of the @NotNull annotation
  - Check that parameter is not null

Steps for making an analysis

- Install Crystal
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- Add annotations
- **Add branch-sensitivity**

Branch-sensitivity

- Take advantage of knowledge gained through tests
- Specify different exit paths through a method
  - An invariant that doesn't hold on exceptional exit
- Labeled branches let us distinguish these
- **Must return different lattice elements for each label**

```
if (x != null) {
  //hey, it's safe
  //to use x in here!
}
else {
  //but it's an
  //error in here!
}
```

On paper…

- No branch sensitivity

  $f(x == y, \sigma) = \sigma$

- Branch sensitivity

  $f^{T}(x == y, \sigma) =$

  if ($\sigma(x) <$ MAYBE_NULL)

  $\sigma[y \rightarrow \sigma(x)]$

  else if ($\sigma(y) <$ MAYBE_NULL)

  $\sigma[x \rightarrow \sigma(y)]$

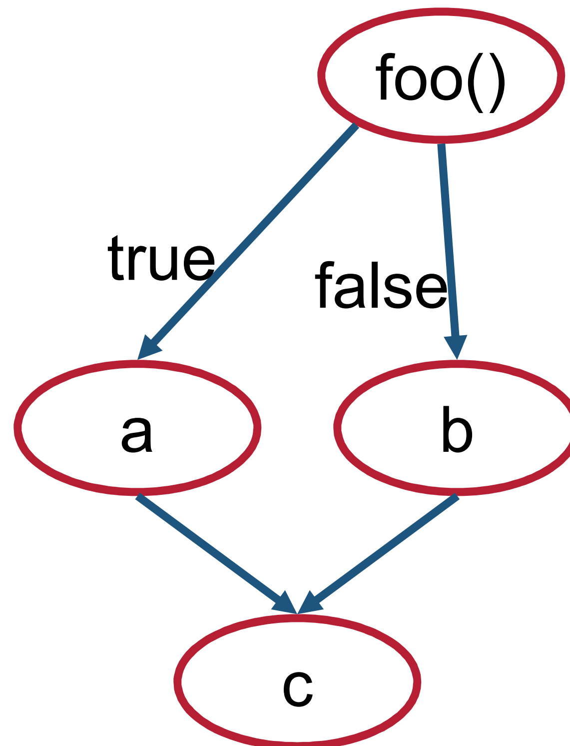
  else

  σ

- Separate definition for the false branch $f^{F}(x == y, \sigma)$

Branching example

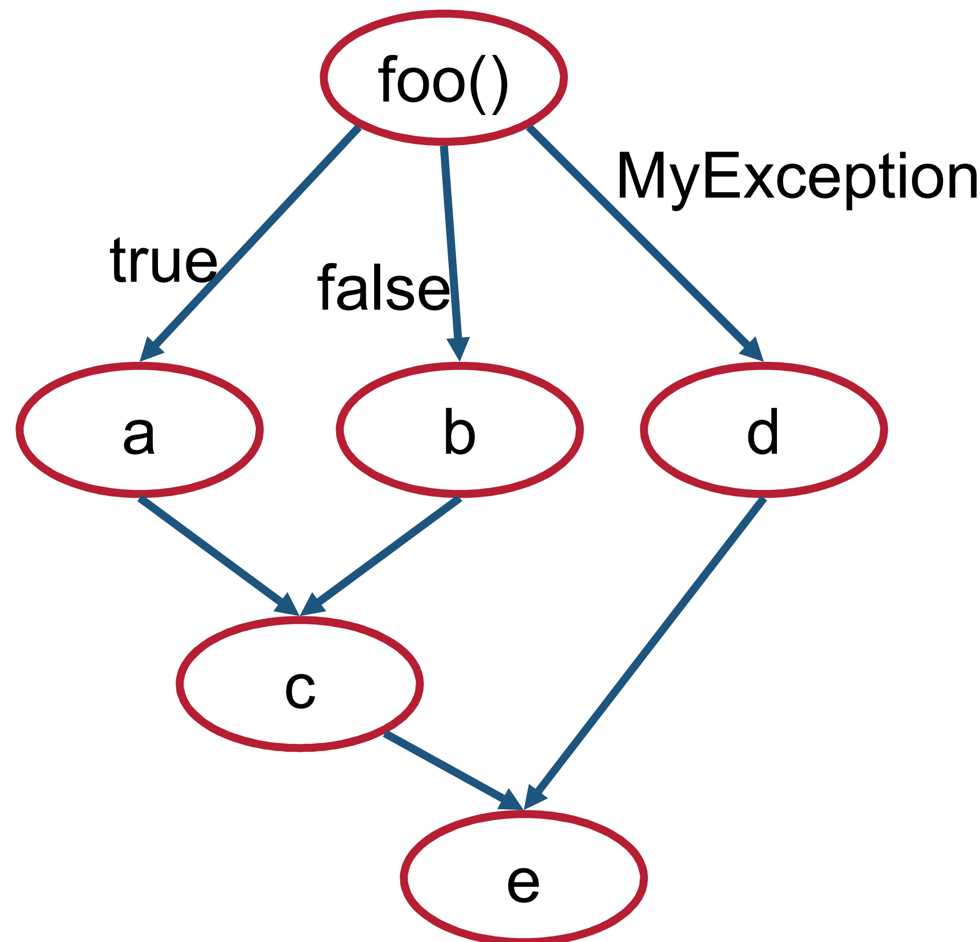
```
if (foo()) {
   a;
}
else {
   b;
}
c;
```




```
public boolean foo()
```

Branching example, with exceptions

```
try {
   if (foo()) {
      a;
   }
   else {
      b;
   }
   c;
}
catch (MyException exp) {
   d;
}
e;
```




```
public boolean foo() throws MyException;
```

Types of labels

- True/false
  - All conditionals (if, while, ?:, etc.)
  - Methods calls that return a boolean
  - Binary relational operators (&&, <, ==, etc.)
- Exceptional
  - Methods calls that throw exceptions
  - Throw statements
  - Catch and Finally statements
- Switch (used on switch)
- Iterator (used on enhanced for)
- Normal

Changing to branch-sensitive analyses

1. Implement AbstractTACBranchSensitiveTransferFunction
2. Change signatures on transfer functions

```
public LE transfer(TACInstruction instr, LE value)
```

```
public IResult<LE> transfer(TACInstruction instr,
                List<ILabel> labels, LE value)
```

3. Wrap return lattice in an IResult

```
return value;
```

```
return LabeledSingleResult.createResult(value, labels);
```

At this point, transfer functions run as they did before

Using the branches

- **Which instructions can provide different information on each branch?**
  - x == y
  - x != y

- **Create a new LabeledResult with the labels and a default value**
  - Copy the lattice element for each branch
  - Change the lattice elements
  - Put them into the labeled result with the right label

Crystal Static Analysis Framework

- Fast startup into a simple analysis
- Direct from theory to implementation
- Incremental sophistication of analysis
- Full power of Eclipse infrastructure
- **Proven useful for both teaching and research**
  - 4 research analyses
  - Used for several years in a professional master's course