Formal Verification of OO Programs: the Krakatoa Approach

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Outline

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Krakatoa

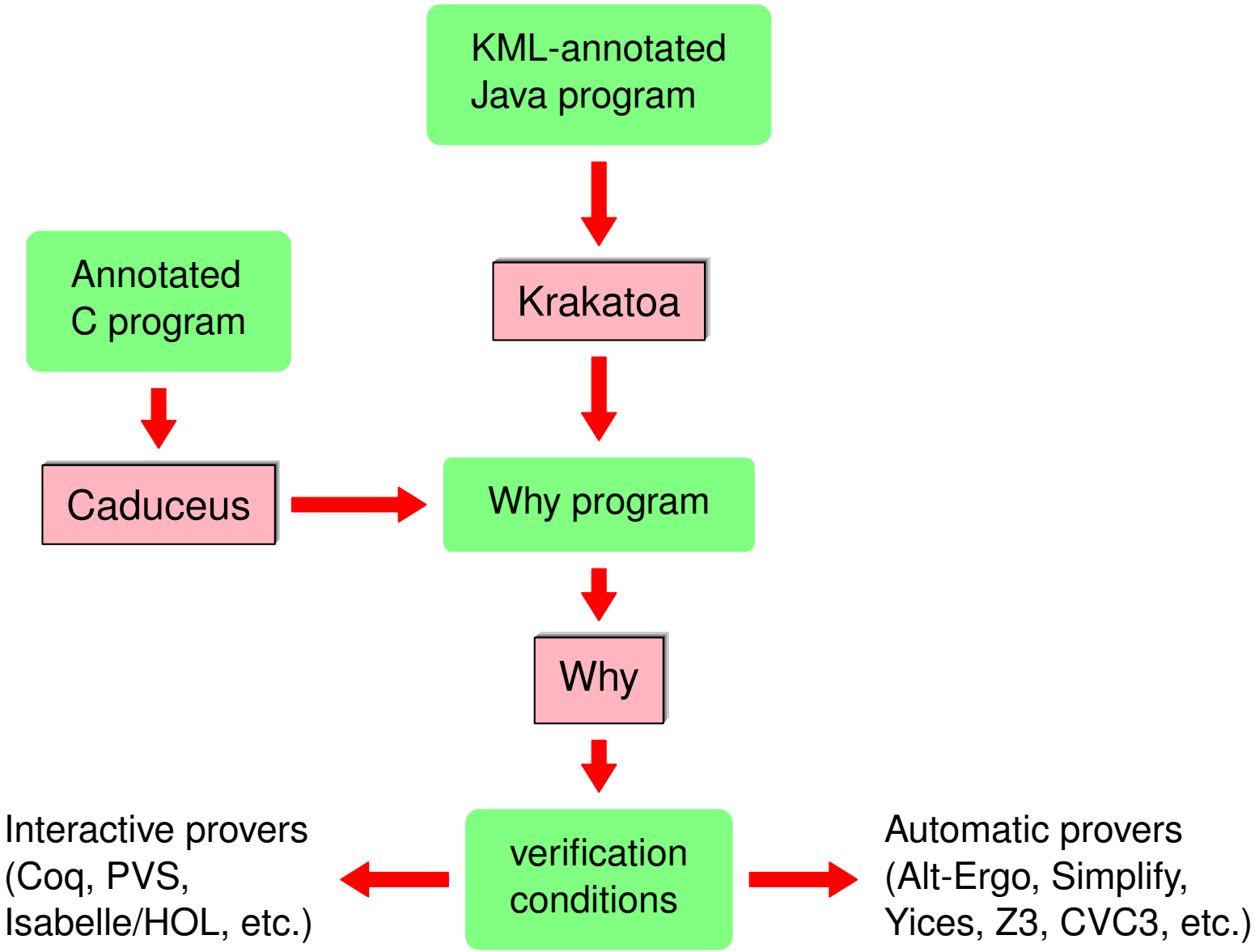
Krakatoa is a deductive verification tool for Java(Card) programs

- Specifications as annotations
- Verification Conditions generated using a weakest precondition calculus (Why VCgen)

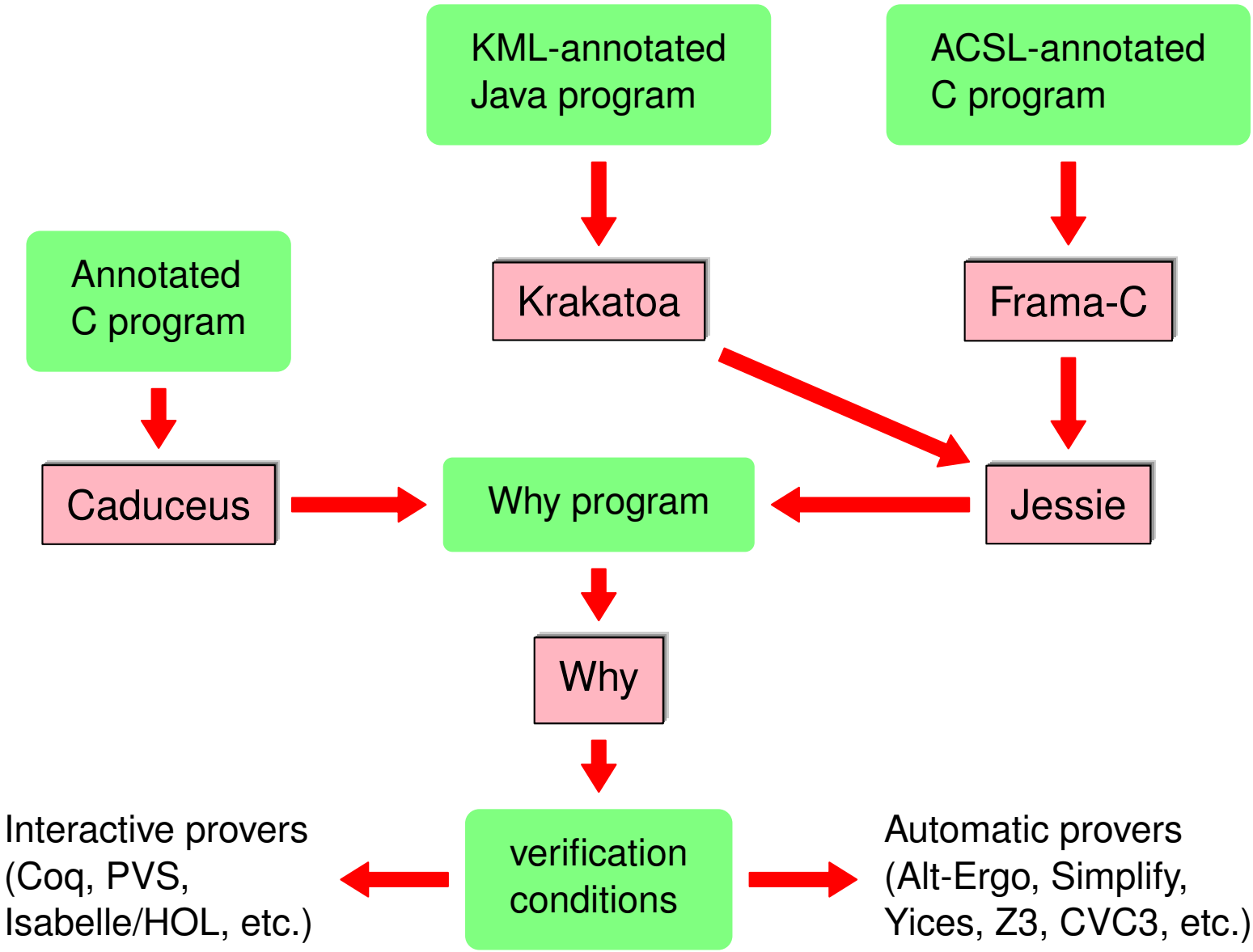
Krakatoa is just one tool of the Why platform which has

- several languages input
- several prover output

Architecture (2004)



Architecture (2008)



First example: isqrt

```
public static int isqrt(int x) {
    int count = 0, sum = 1;
    while (sum <= x) {
        count++;
        sum = sum + 2*count+1;
    }
    return count;
}
```

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KML: Krakatoa Modeling Language

- Largely inspired from the JML (*Java Modeling Language*)
- Shares many features with the ACSL (*ANSI/ISO C Specification Language*), the specification language of Frama-C, e.g.:
  - Contracts with named behaviors
  - Algebraic-style specifications

Method Contracts

Simple form:

```
/*@ requires R;
  @ assigns A;
  @ ensures E;
  @*/
```

- R: precondition, supposed to hold in the *pre-state*
  Must be checked valid *by the caller*
- E: postcondition, supposed to hold in the *post-state*
- A: set of possibly modified memory locations

Special keywords in E:

- `\result`: denotes the returned value
- `\old`(e): denotes the value of e in the pre-state.

Method Contracts

General form of contracts:

```
/*@ requires R;
  @ behavior b1:
  @ ...
  @ behavior b2:
  @ ...
  @*/
```

$b_1, b_2, \ldots$ is a set of named behaviors.

Normal behaviors

A *normal* behavior has the form:

```
/*@ ...
  @ behavior b:
  @   assumes A;
  @   assigns L;
  @   ensures E;
  @*/
```

It states that:

- In the post-state: `\old`(A)==>E holds
- If A holds in the pre-state: each memory location not in L is unmodified.

Exceptional behaviors

An *exceptional* behavior has the form

```
/*@ ...
  @ behavior b:
  @   assumes A;
  @   assigns L;
  @   signals (Exc x) E;
  @*/
```

States the same properties as a normal behavior, but in the case the method returns abruptly with exception *Exc*.

Class invariants

A *class invariant* is declared at the level of class fields, with a name:

`/*@ invariant` *id*`:` *e*`;`

- Warning: Krakatoa handles those invariants just as "macros" for pre- and post-conditions of methods

Example: Toy Electronic Purse

```
public class Purse {

    private int balance;
    /*@ invariant balance_positive:
      @   balance > 0;
      @*/

    /*@ requires amount > 0;
      @ assigns balance;
      @ ensures balance == amount;
      @*/
    public Purse(int amount) {
        balance = amount;
    }
```

Example: Toy Electronic Purse

```
/*@ requires s >= 0;
  @ assigns balance;
  @ ensures balance == \old(balance) + s;
  @*/
public void credit(int s) {
    balance += s;
}
```

Example: Toy Electronic Purse

```
/*@ requires s >= 0;
  @ assigns balance;
  @ ensures s < \old(balance) &&
  @   balance == \old(balance) - s;
  @ behavior amount_too_large:
  @   assigns \nothing;
  @   signals (NoCreditException)
  @     s >= \old(balance) ;
  @*/
public void withdraw(int s)
    throws NoCreditException {
    if (s < balance)
        balance = balance - s;
    else
        throw new NoCreditException();
}
```

Statement Annotations

- Assertions:

  `//@ assert p;`

  $\rightsquigarrow$ p holds at this program point.
- Loop annotations:

  `/*@ loop_invariant` I
  `@ for` b`: loop_invariant` I_b`;`
  `@ loop_variant` V`;`
  `@*/`
- I holds at loop entry
- I preserved by any iteration of the loop body
- I_b, same as I, but under `assumes` A of behavior b.
- V integer expression which decrease at each loop iteration, and remains non-negative

Logic definitions

- KML does not allow *pure* methods in annotations.
- But allows to declare new logic functions and predicates:

  `//@ logic` τ $id(\tau_1\ x_1, \ldots, \tau_n\ x_n) = e$;
  `//@ predicate` $id(\tau_1\ x_1, \ldots, \tau_n\ x_n) = p$;
- Types τ and τ_i: Java types or purely logic types: `integer`, `real`, etc.
- Lemmas:

  `//@ lemma id:` p;

Example: Sorting Algorithm

- We want to express the behavior: resulting array is in increasing order
- We declare a predicate `sorted` for that purpose

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Hybrid predicates

- `sorted` is a *hybrid* predicate: it depends on some memory state.
- More generally, we can have predicates depending on *several* memory states, by attaching several labels.

```
/*@ logic τ id{L_1,...,L_k}(τ_1 x_1,...,τ_n x_n) =
  @     e;
  @*/
/*@ predicate id{L_1,...,L_k}(τ_1 x_1,...,τ_n x_n) =
  @   p;
  @*/
```

Inductive predicates

/*@ inductive $P(\tau_1\ x_1, \ldots, \tau_n\ x_n)$ {
  @ case c_1 : p_1;
...
  @ case c_k : p_k;
  @ }
  @*/

- P is the least fixpoint of the cases
- each proposition p_i must have the form

  \forall $y_1, \ldots, y_m$,
    h_1 ==> $\cdots$ ==> h_l ==> $P(t_1, \ldots, t_n)$

  where P occurs only positively in hypotheses $h_1, \ldots, h_l$.

Example: Sorting Algorithm

- New behavior: the resulting array is a permutation of the original one
- We declare `permut` as an inductive, two-state predicate

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Axiomatic blocks

```
axiomatic Power {
  logic real lpower(real x, integer n);
  axiom power_zero:
    \forall real x; lpower(x,0) == 1.0;
  axiom power_one:
    \forall real x; lpower(x,1) == x;
  axiom power_sum:  ...
}
```

- type names
- profiles for predicates and logic functions
- axioms they satisfy

Warning! no guarantee of consistency

Outline

Why: a Verification Condition Generator

Why is a *verification condition generator* for a language with

- variables containing pure values, no alias
  ($\sim$ Hoare-logic language)
- basic control structures: tests, (infinite) loops
- exceptions
- (possibly recursive) functions
- polymorphic first-order logic with equality and arithmetic

Why is similar to Boogie (SPEC# project)
Why is also responsible for *translating* verification conditions to the *native logics* of all provers

Basic Idea

makes program verification

- prover-independent but prover-aware
- language-independent

so that we can use it to verify C, Java, etc. programs with HOL provers but also with FO decision procedures

The essence of Hoare logic: assignment rule

$$\{\ P[x \leftarrow E]\ \}\ x\ :=\ E\ \{\ P\ \}$$

1. absence of aliasing
2. side-effects free E *shared* between program and logic

Data types

Any purely applicative data type from the logic can be used in programs
Example: a data type `int` for integers with constants `0`, `1`, etc. and operations `+`, `*`, etc.
The pure expression *`1+2`* belongs to both programs and logic
Only one data structure:

- *reference* (mutable variable) containing *only pure values*
- no alias allowed between two different references

ML syntax

No distinction between expressions and statements
$\Rightarrow$ less constructs
$\Rightarrow$ less rules

dereference	`!`x
assignment	x `:=` e
local variable	`let` x `=` e_1 `in` e_2
local reference	`let` x `= ref` e_1 `in` e_2
conditional	`if` e_1 `then` e_2 `else` e_3
loop	`loop` e

syntactic sugar, e.g.:

sequence e_1 `;` e_2 $\equiv$ `let _ =` e_1 `in` e_2

Annotations

Assertions, post-conditions:

- `assert` $\{p\}$; e
- e $\{p\}$

Examples:

- `assert` $\{!x > 0\}$; $1/!x$
- $!x + 1$ $\{result = !x + 1\}$
- $x := !x + 1$ $\{!x = x@ + 1\}$

Loop invariant and variant:

- `loop` e $\{$`invariant` p `variant` $t\}$

Functions

A function declaration introduces a *precondition*

- $\texttt{fun}\ (x : \tau) \rightarrow \{p\}\ e$

Example:

$$\texttt{fun}\ (x : \texttt{int ref}) \rightarrow \{\,!x > 0\}\ x := !x - 1\ \{!x \geq 0\}$$

Function call:

- $e_1\ e_2$: e_1 applied to e_2
- sugar: $(e\ e_1\ e_2\ \cdots\ e_n)$: e applied to $e_1, \ldots, e_n$

Exceptions

new constructs

- `raise` $(E\ e) : \tau$
- `try` e_1 `with` $E\ x \rightarrow e_2$ `end`

The notion of postcondition is extended

`if` $x < 0$ `then raise` Negative `else` *sqrt* x
$\{\ result \geq 0 \mid \text{Negative} \Rightarrow x < 0\ \}$

Example: isqrt

```
exception Break of unit

let isqrt= fun (x:int) ->
  { x >= 0 }
  let count = ref 0 in
  let sum = ref 1 in
  try
    loop
      if sum > x then raise Break;
      count := !count + 1;
      sum := !sum + 2 * !count + 1;
    { invariant count >= 0
        and x >= sqr(count)
        and sum = sqr(count+1)
      variant x - sum }
  with Break -> void;
  !count
  { result >=0 and sqr(result) <= x
    and x < sqr(result + 1) }
```

Modularity

A function declaration extends the ML function type with a *precondition*, an *effect* and a *postcondition*

$$
\begin{array}{lll}
f : & x : \tau_1 & \rightarrow \quad \{p\} \\
 & & \quad \tau_2 \\
 & & \quad \texttt{reads}\, x_1, \ldots, x_n \\
 & & \quad \texttt{writes}\, y_1, \ldots, y_m \\
 & & \quad \texttt{raises}\, E_1, \ldots, E_k \\
 & & \quad \{q | E_1 \Rightarrow q_1, \ldots, E_k \Rightarrow q_k\}
\end{array}
$$

Examples:

$$
\begin{array}{l}
\mathit{swap} : \; x : \texttt{int}\ \text{ref} \rightarrow y : \texttt{int}\ \text{ref} \rightarrow \\
\qquad \{\}\, \texttt{unit}\ \texttt{writes}\ x, y\, \{x = y@ \wedge y = x@\} \\
\mathit{div} : \; x : \texttt{int} \rightarrow y : \texttt{int} \rightarrow \\
\{\}\, \texttt{int}\ \texttt{raises}\ \text{Negative}\, \{\ldots | \text{Negative} \Rightarrow y = 0\}
\end{array}
$$

Typing

Typing judgment

$$\Gamma \vdash e : (\tau, \epsilon)$$

Rules given in the lecture notes

Important: *typing excludes aliasing*:

$$\begin{array}{l} \mathit{let}\ \mathit{incr} = \mathit{fun}(x : \texttt{int}\ \mathsf{ref})(y : \texttt{int}\ \mathsf{ref}) \rightarrow \\ \qquad \{\}x := !x + 1; y := !y + 1\{x = x@ + 1 \wedge y = y@ + 1\} \\ \mathit{let}\ \_ = (\mathit{incr}\ z\ z) \end{array}$$

$\rightsquigarrow$ error: application creates an alias

Semantics

Call-by-value semantics, with left to right evalutation

Big-step operational semantics given in the lecture notes

Proof Rules: Weakest Preconditions

- $wp(e, q)$: the *weakest precondition* for program e and postcondition q
- *Property:* If $wp(e, q)$ holds, then e terminates and q holds at the end of execution (and all inner annotations are verified)
- The correctness of an annotated program e is thus $wp(e, \text{True})$

Definition of $wp(e, q)$

We actually define $wp(e, q; r)$ where

- q is the "normal" postcondition
- $r \equiv E_1 \Rightarrow q_1; \ldots; E_n \Rightarrow q_n$ is the set of "exceptional" post.

WP rules: excerpt

- pure expressions:

$$wp(u, q; r) = q[result \leftarrow u]$$

- assignment:

$$wp(x := e, q; r) = wp(e, q[!x \leftarrow result]; r)$$

- if statement:

$$wp(\texttt{if } e_1 \texttt{ then } e_2 \texttt{ else } e_3, q; r) = wp(e_1, \texttt{if } result \texttt{ then } wp(e_2, q; r) \texttt{ else } wp(e_3, q; r);$$

Note: this is the “natural” WP rule for if. There exists an “efficient” one [Leino03]

Exceptions

- if e is pure:

$$wp(\texttt{raise}\ (E\ e) : \tau, q; r; E \Rightarrow r_E) = r_E$$

- in general:

$$wp(\texttt{raise}\ (E\ e) : \tau, q; r; E \Rightarrow r_E) = wp(e, r_E; r)$$

- exception catching:

$$wp(\texttt{try}\ e_1\ \texttt{with}\ E\ x \rightarrow e_2\ \texttt{end}, q; r) = wp(e_1, q; E \Rightarrow wp(e_2, q; r)[x \leftarrow result]; r)$$

Annotations

$$wp(\texttt{assert}\ \{p\};\ e, q; r) = p \wedge wp(e, q; r)$$

$$wp(e\ \{q'; r'\}, q; r) = wp(e, q' \wedge q; r' \wedge r)$$

Loops

- loop without variant:

$$wp(\texttt{loop}\ e\ \{\texttt{invariant}\ p\}, q; r) = \\ p\ \wedge\ \forall \omega.\ p \Rightarrow wp(e, p; r)$$

  where ω = the variables (possibly) modified by e
- loop with variant: see lecture notes.

Functions

- Function call: first simplified as

$$e_1\ e_2 \equiv \texttt{let}\ x_1 = e_1\ \texttt{in let}\ x_2 = e_2\ \texttt{in}\ x_1\ x_2$$

- then, assuming $x_1 \ : \ (x : \tau) \rightarrow \{p'\}\,\tau'\,\epsilon\,\{q'\}$

$$wp(x_1\ x_2, q) = \\ p'[x \leftarrow x_2] \ \wedge \ \forall\omega.\forall result.(q'[x \leftarrow x_2] \Rightarrow q)[t@ \leftarrow t]$$

Outline

Krakatoa to Why

Delayed to lecture 2

End of lecture 1

- Krakatoa installation, exercises:
  `http://krakatoa.lri.fr/ws`
- Try to solve exercises before the lab session
- Challenge: solve the “mystery code” exercise