More data types (lists, trees)
Handling Exceptions
Computer Arithmetic

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Cours MPRI 2-36-1 “Preuve de Programme”

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Outline

Reminders, Solutions to Exercises
- Function calls
- Termination
- Axiomatizations, Ghost Code
- Ghost Functions, Lemma Functions
- Programs on Arrays

Modeling Continued: Specifying More Data Types
- Sum Types
- Lists

Exceptions

Application: Computer Arithmetic
- Handling Machine Integers
- Floating-Point Computations

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Function Calls

let $f(x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau$
  requires Pre
  writes $\vec{w}$
  ensures $Post$
  body $Body$

$$\begin{aligned} \mathrm{WP}(f(t_1, \ldots, t_n), Q) = {} & Pre[x_i \leftarrow t_i] \wedge \\ & \forall \vec{v},\ (Post[x_i \leftarrow t_i, w_j \leftarrow v_j, w_j@Old \leftarrow w_j] \rightarrow Q[w_j \leftarrow v_j]) \end{aligned}$$

Modular proof

When calling function f, only the contract of f is visible, not its body

Soundness Theorem for a Complete Program

Assuming that for each function defined as

let $f(x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau$
requires Pre
writes $\vec{w}$
ensures $Post$
body $Body$

we have

- variables assigned in $Body$ belong to $\vec{w}$,
- $\models Pre \rightarrow \mathrm{WP}(Body, Post)[w_i@Old \leftarrow w_i]$ holds,

then for any formula Q and any expression e,
if $\Sigma, \Pi \models \mathrm{WP}(e, Q)$ then execution of Σ, Π, e is *safe*

Remark: (mutually) recursive functions are allowed

Termination

- Loop *variant*
- *Variants* for (mutually) recursive function(s)

Home Work 1: McCarthy's 91 Function

$$f91(n) = \texttt{if } n \leq 100 \texttt{ then } f91(f91(n+11)) \texttt{ else } n - 10$$

Find adequate specifications

```
let f91(n:int): int
  requires ?
  variant ?
  writes ?
  ensures ?
body
  if n ≤ 100 then f91(f91(n + 11)) else n - 10
```

Use canvas file `mccarthy.mlw`

Why3 Logic Language

- (First-order) logic, built-in arithmetic (integers and reals)
- *Definitions* à la ML
  - logic (i.e. pure) *functions, predicates*
  - structured types, pattern-matching (this lecture!)
- *type polymorphism* à la ML
- *higher-order logic as a built-in theory of functions*
- Axiomatizations
- Inductive predicates (not detailed here)

Important note

Logic functions and predicates are *always totally defined*

Ghost Code

Ghost code, ghost variables

- Cannot interfere with regular code (checked by typing)
- Visible only in annotations

Home Work 2

- Extend the post-condition of Euclid's algorithm for GCD to express the Bézout property:

$$\exists a, b, result = x * a + y * b$$

- Prove the program by adding appropriate ghost local variables

Use canvas file `exo_bezout.mlw`

Axiomatic Definitions

- logic functions, predicates without body
- axioms to specify their behavior
- axiomatic types
- Risk of inconsistency

Example: division

```
function div(real,real):real
axiom mul_div:
  forall x,y. y≠0 → div(x,y)*y = x
```

Error "Division by zero" can be modeled by an abstract function

```
val div_real(x:real,y:real):real
   requires y ≠ 0.0
   ensures  result = div(x,y)
```

Reminder

Execution blocks when an invalid annotation is met

More Ghosts: Programs turned into Logic Functions

If the program f is

- *Proved terminating*
- *Has no side effects*

```
let f(x_1 : τ_1, ..., x_n : τ_n) : τ
  requires Pre
  variant var, ≺
  ensures Post
  body Body
```

then there exists a logic function:

function $f\ \tau_1\ \ldots\ \tau_n\ :\ \tau$
lemma $f_{spec} : \forall x_1, \ldots, x_n.\ Pre \rightarrow Post[\texttt{result} \leftarrow f(x_1, \ldots, x_n)]$

and if *Body* is a pure term then

lemma $f_{body} : \forall x_1, \ldots, x_n.\ Pre \rightarrow f(x_1, \ldots, x_n) = Body$

Offers an important alternative to axiomatic definitions

In Why3: done using keywords `let function`

Example: axiom-free specification of factorial

```
let function fact (n:int) : int
  requires { n ≥ 0 }
  variant { n }
= if n=0 then 1 else n * fact(n-1)
```

generates the logic context

```
function fact int : int

axiom f_body: forall n. n ≥ 0 →
  fact n = if n=0 then 1 else n * fact(n-1)
```

Example of Factorial

Exercise: Find appropriate precondition, postcondition, loop invariant, and variant, for this program:

```
let fact_imp (x:int): int
  requires ?
  ensures ?
body
  let ref y = 0 in
  let ref res = 1 in
  while y < x do
    y <- y + 1;
    res <- res * y
  done;
  res
```

See file `fact.mlw`

More Ghosts: Lemma functions

- if a program function is *without side effects* and *terminating*:

  let $f(x_1 : \tau_1, \ldots, x_n : \tau_n) : \texttt{unit}$
  requires Pre
  variant $var, \prec$
  ensures $Post$
  body $Body$

  then it is a proof of

$$\forall x_1, \ldots, x_n . Pre \rightarrow Post$$

- If f is recursive, it simulates a proof by induction

Home work 3

Prove the helper lemmas stated for the fast exponentiation algorithm

See `power_int_lemma_functions.mlw`

Home Work 4

Prove Fermat's little theorem for case $p = 3$:

$$\forall x, \exists y. x^3 - x = 3y$$

using a lemma function

See `little_fermat_3.mlw`

Programs on Arrays

- applicative maps as a built-in theory
- array = record (length, pure map)
- handling of out-of-bounds index check

```
type array α = { length : int; elts : int → α}

val get (ref a:array α) (i:int) : α
  requires 0 ≤ i < a.length
  ensures  result = select(a.elts,i)

val set (ref a:array α) (i:int) (v:α) : unit
  requires 0 ≤ i < a.length
  writes   a
  ensures  a.length = a@Old.length ∧
           a.elts = store(a@Old.elts,i,v)
```

- `a[i]` interpreted as a call to `get(a,i)`
- `a[i] <- v` interpreted as a call to `set(a,i,v)`

Exercise: Search Algorithms

```
var a: array real

let search(v:real): int
  requires 0 ≤ a.length
  ensures  { ? }
= ?
```

1. Formalize postcondition: if v occurs in a, between 0 and $a.length - 1$, then result is an index where v occurs, otherwise result is set to -1
2. Implement and prove *linear search*:

   $res \leftarrow -1$;
   for each i from 0 to $a.length - 1$: if $a[i] = v$ then $res \leftarrow i$;
   return res

See file `lin_search.mlw`

Home Work: Binary Search

$low = 0$; $high = a.length - 1$;
while $low \leq high$:
   let m be the middle of *low* and *high*
   if $a[m] = v$ then return m
   if $a[m] < v$ then continue search between m and *high*
   if $a[m] > v$ then continue search between *low* and m

See file `bin_search.mlw`

Home Work: "for" loops

Syntax: $\texttt{for } i = e_1 \texttt{ to } e_2 \texttt{ do } e$

Typing:

- i visible only in e, and is immutable
- e_1 and e_2 must be of type `int`, e must be of type `unit`

Operational semantics:
(assuming e_1 and e_2 are values v_1 and v_2)

$$\frac{v_1 > v_2}{\Sigma, \Pi, \texttt{for } i = v_1 \texttt{ to } v_2 \texttt{ do } e \rightsquigarrow \Sigma, \Pi, ()}$$

$$\frac{v_1 \leq v_2}{\Sigma, \Pi, \texttt{for } i = v_1 \texttt{ to } v_2 \texttt{ do } e \rightsquigarrow \Sigma, \Pi, \begin{array}{l}(\texttt{let } i = v_1 \texttt{ in } e); \\ (\texttt{for } i = v_1 + 1 \texttt{ to } v_2 \texttt{ do } e)\end{array}}$$

Home Work: “for” loops

Propose a Hoare logic rule for the `for` loop:

$$\frac{\{?\}e\{?\}}{\{?\}\texttt{for}\ i = v_1\ \texttt{to}\ v_2\ \texttt{do}\ e\{?\}}$$

Propose a rule for computing the WP:

$$\mathrm{WP}(\texttt{for}\ i = v_1\ \texttt{to}\ v_2\ \texttt{invariant}\ I\ \texttt{do}\ e, Q) = ?$$

Home Work: "for" loops

Notice: loop invariant I typically has i as a free variable
Informal vision of execution, stating when invariant is supposed to hold and for which value of i:

$\{I[i \leftarrow v1]\}$
$i \leftarrow v1$
$\{I\}$
e
$\{I[i \leftarrow i+1]\}$
$i \leftarrow i+1$
$\{I\}$
e
$\vdots$
$\{I\}$
e
$\{I[i \leftarrow i+1]\}$
$i \leftarrow i+1$
(* assuming now $i = v2$, last iteration *)
$\{I\}$(* where $i = v2$ *)
e
$\{I[i \leftarrow i+1]\}$(* and still i=v2, hence *)
$\{I[i \leftarrow v2+1]\}$

Home Work: “for” loops

So we deduce the Hoare logic rule

$$\frac{\{I \wedge v_1 \le i \le v_2\} e \{I[i \leftarrow i+1]\}}{\{I[i \leftarrow v_1] \wedge v_1 \le v_2\} \texttt{for } i = v_1 \texttt{ to } v_2 \texttt{ do } e \{I[i \leftarrow v_2 + 1]\}}$$

Remark

Some rule should be stated for case $v_1 > v_2$, left as exercise

and then a rule for computing the WP:

$$\begin{array}{l}
\mathrm{WP}(\texttt{for } i = v_1 \texttt{ to } v_2 \texttt{ invariant } I \texttt{ do } e, Q) = \\
v_1 \le v_2 \wedge I[i \leftarrow v_1] \wedge \\
\quad \forall \vec{v}, (\\
\qquad (\forall i, I \wedge v_1 \le i \le v_2 \rightarrow \mathrm{WP}(e, I[i \leftarrow i+1])) \wedge \\
\qquad (I[i \leftarrow v_2 + 1] \rightarrow Q))[w_j \leftarrow v_j]
\end{array}$$

Additional exercise: use a for loop in the linear search example

`lin_search_for.mlw`

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Sum Types

- Sum types à la ML:

  type t =
  $| \ C_1 \ \tau_{1,1} \cdots \tau_{1,n_1}$
  $| \ \vdots$
  $| \ C_k \tau_{k,1} \cdots \tau_{k,n_k}$

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  $| \ \vdots$
  $| \ C_k \tau_{k,1} \cdots \tau_{k,n_k}$

- Pattern-matching with

  match e with
  $| \ C_1(p_1, \cdots, p_{n_1}) \to e_1$
  $| \ \vdots$
  $| \ C_k(p_1, \cdots, p_{n_k}) \to e_k$
  end

Sum Types

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  $| \ \vdots$
  $| \ C_k(p_1, \cdots, p_{n_k}) \rightarrow e_k$
  end

- Extended pattern-matching, wildcard: _

Recursive Sum Types

- Sum types can be recursive.
- Recursive definitions of functions or predicates
  - Must terminate (only total functions in the logic)
  - In practice in Why3: recursive calls only allowed on structurally smaller arguments.

Sum Types: Example of Lists

```
type list α = Nil | Cons α (list α)

function append(l1:list α,l2:list α): list α =
  match l1 with
  | Nil → l2
  | Cons(x,l) → Cons(x, append(l,l2))
  end

function length(l:list α): int =
  match l with
  | Nil → 0
  | Cons(_,r) → 1 + length r
  end

function rev(l:list α): list α =
  match l with
  | Nil → Nil
  | Cons(x,r) → append(rev(r), Cons(x,Nil))
  end
```

"In-place" List Reversal

Exercise: fill the holes below.

```
val ref l: list int

let rev_append(r:list int)
  variant ?  writes  ?   ensures ?
body
  match r with
  | Nil → ()
  | Cons(x,r) → l <- Cons(x,l); rev_append(r)
  end

let reverse(r:list int)
  writes l  ensures l = rev r
body ?
```

See `rev.mlw`

Binary Trees

```
type tree α = Leaf | Node (tree α) α (tree α)
```

Home work: specify, implement, and prove a procedure returning the maximum of a tree of integers.

(problem 2 of the FoVeOOS verification competition in 2011, `http://foveoos2011.cost-ic0701.org/verification-competition`)

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Exceptions

We extend the syntax of expressions with

$$\begin{array}{lcl} e & ::= & \texttt{raise}\ \mathit{exn} \\ & | & \texttt{try}\ e\ \texttt{with}\ \mathit{exn} \rightarrow e \end{array}$$

with *exn* a set of exception identifiers, declared as

```
exception exn <type>
```

Remark: `<type>` can be omitted if it is `unit`
Example: linear search revisited in `lin_search_exc.mlw`

Operational Semantics

- Values: either constants v or $\texttt{raise}\ exn$

Propagation of thrown exceptions:

$$\Sigma, \Pi, (\texttt{let}\ x = \texttt{raise}\ exn\ \texttt{in}\ e) \rightsquigarrow \Sigma, \Pi, \texttt{raise}\ exn$$

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Reduction of try-with:

$$\frac{\Sigma, \Pi, e \rightsquigarrow \Sigma', \Pi', e'}{\Sigma, \Pi, (\texttt{try}\ e\ \texttt{with}\ exn \rightarrow e'') \rightsquigarrow \Sigma', \Pi', (\texttt{try}\ e'\ \texttt{with}\ exn \rightarrow e'')}$$

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Normal execution:

$$\Sigma, \Pi, (\texttt{try}\ v\ \texttt{with}\ exn \rightarrow e') \rightsquigarrow \Sigma, \Pi, v$$

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Normal execution:

$$\Sigma, \Pi, (\texttt{try}\ v\ \texttt{with}\ exn \to e') \rightsquigarrow \Sigma, \Pi, v$$

Exception handling:

$$\Sigma, \Pi, (\texttt{try}\ \texttt{raise}\ exn\ \texttt{with}\ exn \to e) \rightsquigarrow \Sigma, \Pi, e$$

$$\frac{exn \neq exn'}{\Sigma, \Pi, (\texttt{try}\ \texttt{raise}\ exn\ \texttt{with}\ exn' \to e) \rightsquigarrow \Sigma, \Pi, \texttt{raise}\ exn}$$

WP Rules

Function WP modified to allow exceptional post-conditions too:

$$\mathrm{WP}(e, Q, exn_i \to R_i)$$

Implicitly, $R_k = False$ for any $exn_k \notin \{exn_i\}$.

WP Rules

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$$\mathrm{WP}(e, Q, exn_i \rightarrow R_i)$$

Implicitly, $R_k = \mathit{False}$ for any $exn_k \notin \{exn_i\}$.

Extension of WP for simple expressions:

$$\mathrm{WP}(x \mathrel{<\!\!-} t, Q, exn_i \rightarrow R_i) = Q[\mathrm{result} \leftarrow (), x \leftarrow t]$$

$$\mathrm{WP}(\mathtt{assert}\ R, Q, exn_i \rightarrow R_i) = R \wedge Q$$

WP Rules

Extension of WP for composite expressions:

$$\begin{array}{l}\mathrm{WP}(\texttt{let}\ x = e_1\ \texttt{in}\ e_2, Q, exn_i \to R_i) = \\ \qquad \mathrm{WP}(e_1, \mathrm{WP}(e_2, Q, exn_i \to R_i)[\text{result} \leftarrow x], exn_i \to R_i)\end{array}$$

$$\begin{array}{l}\mathrm{WP}(\texttt{if}\ t\ \texttt{then}\ e_1\ \texttt{else}\ e_2, Q, exn_i \to R_i) = \\ \qquad \texttt{if}\ t\ \texttt{then}\ \mathrm{WP}(e_1, Q, exn_i \to R_i) \\ \qquad\qquad \texttt{else}\ \mathrm{WP}(e_2, Q, exn_i \to R_i)\end{array}$$

$$\begin{array}{l}\mathrm{WP}\left(\begin{array}{c}\texttt{while}\ c\ \texttt{invariant}\ I \\ \texttt{do}\ e\end{array}, Q, exn_i \to R_i\right) = I \land \forall \vec{v}, \\ \qquad (I \to \texttt{if}\ c\ \texttt{then}\ \mathrm{WP}(e, I, exn_i \to R_i)\ \texttt{else}\ Q)[w_i \leftarrow v_i]\end{array}$$

where $w_1, \ldots, w_k$ is the set of assigned variables in e and $v_1, \ldots, v_k$ are fresh logic variables.

WP Rules

Exercise: propose rules for

$$\mathrm{WP}(\texttt{raise}\ \mathit{exn}, Q, \mathit{exn}_i \to R_i)$$

and

$$\mathrm{WP}(\texttt{try}\ e_1\ \texttt{with}\ \mathit{exn} \to e_2, Q, \mathit{exn}_i \to R_i)$$

WP Rules

$$\mathrm{WP}(\texttt{raise}\ exn_k, Q, exn_i \to R_i) = R_k$$

$$\mathrm{WP}((\texttt{try}\ e_1\ \texttt{with}\ exn \to e_2), Q, exn_i \to R_i) =$$

$$\mathrm{WP}\left(e_1, Q, \left\{\begin{array}{l} exn \to \mathrm{WP}(e_2, Q, exn_i \to R_i) \\ exn_i \backslash exn \to R_i \end{array}\right.\right)$$

Functions Throwing Exceptions

Generalized contract:

$$
\begin{array}{l}
\texttt{val}\ f(x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau \\
\quad \texttt{requires}\ \mathit{Pre} \\
\quad \texttt{writes}\ \vec{w} \\
\quad \texttt{ensures}\ \mathit{Post} \\
\quad \texttt{raises}\ E_1 \to \mathit{Post}_1 \\
\quad \vdots \\
\quad \texttt{raises}\ E_n \to \mathit{Post}_n
\end{array}
$$

Extended WP rule for function call:

$$
\begin{array}{rl}
\mathrm{WP}(f(t_1, \ldots, t_n), Q, E_k \to R_k) = & \mathit{Pre}[x_i \leftarrow t_i] \wedge \forall \vec{v}, \\
& (\mathit{Post}[x_i \leftarrow t_i, w_j \leftarrow v_j] \to Q[w_j \leftarrow v_j]) \wedge \\
& \bigwedge_k (\mathit{Post}_k[x_i \leftarrow t_i, w_j \leftarrow v_j] \to R_k[w_j \leftarrow v_j])
\end{array}
$$

Verification Conditions for programs

For each function defined with generalized contract

```
let f(x_1 : τ_1, ..., x_n : τ_n) : τ
  requires Pre
  writes w⃗
  ensures Post
  raises E_1 → Post_1
  ⋮
  raises E_n → Post_n
  body Body
```

we have to check

- Variables assigned in *Body* belong to $\vec{w}$
- $\mathit{Pre} \rightarrow \mathrm{WP}(\mathit{Body}, \mathit{Post}, E_k \rightarrow \mathit{Post}_k)[w_i@\mathit{Old} \leftarrow w_i]$ holds

Example: "Defensive" variant of ISQRT

```
exception NotSquare

let isqrt(x:int): int
  ensures result ≥ 0 ∧ sqr(result) = x
  raises  NotSquare → forall n:int. sqr(n) ≠ x
body
  if x < 0 then raise NotSquare;
  let ref res = 0 in
  let ref sum = 1 in
  while sum ≤ x do
    res <- res + 1; sum <- sum + 2 * res + 1
  done;
  if sqr(res) ≠ x then raise NotSquare;
  res
```

See Why3 version in `isqrt_exc.mlw`

Home Work

- Implement and prove binary search using also a immediate exit:

  $low = 0$; $high = a.length - 1$;
  while $low \leq high$:
  let m be the middle of low and $high$
  if $a[m] = v$ then return m
  if $a[m] < v$ then continue search between m and $high$
  if $a[m] > v$ then continue search between low and m

  (see `bin_search_exc.mlw`)

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Computers and Number Representations

- 32-, 64-bit signed integers in two-complement: may *overflow*
  - $2147483647 + 1 \to -2147483648$
  - $100000^2 \to 1410065408$

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- floating-point numbers (32-, 64-bit):
  - *overflows*
    - $2 \times 2 \times \cdots \times 2 \to +\mathit{inf}$
    - $-1/0 \to -\mathit{inf}$
    - $0/0 \to \texttt{NaN}$

Computers and Number Representations

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- floating-point numbers (32-, 64-bit):
  - *overflows*
    - $2 \times 2 \times \cdots \times 2 \rightarrow +\mathit{inf}$
    - $-1/0 \rightarrow -\mathit{inf}$
    - $0/0 \rightarrow$ `NaN`
  - *rounding errors*
    - $\underbrace{0.1 + 0.1 + \cdots + 0.1}_{10 \mathit{times}} = 1.0 \rightarrow$ `false`

      (because $0.1 \rightarrow 0.100000001490116119384765625$ in 32-bit)

See also `arith.c`

Some Numerical Failures

(see more at
http://catless.ncl.ac.uk/php/risks/search.php?query=rounding)

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- 1995, Ariane 5 explodes during its maiden flight due to an overflow: insurance cost is $500M.
- 2007, Excel displays 77.1×850 as 100000.

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  Internal clock ticks every 0.1 second.
  Time is tracked by fixed-point arith.: $0.1 \simeq 209715 \cdot 2^{-24}$.
  Cumulated skew after 24h: -0.08s, distance: 160m.
  System was supposed to be rebooted periodically.

- 2007, Excel displays 77.1×850 as 100000.

  Bug in binary/decimal conversion.
  Failing inputs: 12 FP numbers.
  Probability to uncover them by random testing: 10^{-18}.

Integer overflow: example of Binary Search

- Google "Read All About It: Nearly All Binary Searches and Mergesorts are Broken"

```
let ref l = 0 in
let ref u = a.length - 1 in
while l ≤ u do
  let m = (l + u) / 2 in
  ...
```

$l + u$ may overflow with large arrays!

Goal

prove that a program is safe with respect to overflows

Target Type: int32

- 32-bit signed integers in two-complement representation: integers between -2^{31} and $2^{31} - 1$.
- If the mathematical result of an operation fits in that range, that is the computed result.
- Otherwise, an overflow occurs.
  Behavior depends on language and environment:
  modulo arith, saturated arith, abrupt termination, etc.

A program is safe if no overflow occurs.

Safety Checking

Idea: replace all arithmetic operations by abstract functions with preconditions. $x + y$ becomes $\text{int32\_add}(x, y)$.

```
val int32_add(x: int, y: int): int
  requires -2^31 ≤ x + y < 2^31
  ensures result = x + y
```

Unsatisfactory: range contraints of integer must be added explicitly everywhere

Safety Checking, Second Attempt

Idea:

- replace type *int* with an abstract type *int32*
- introduce a *projection* from *int32* to *int*
- axiom about the *range* of projections of *int32* elements
- replace all operations by abstract functions with preconditions

```
type int32
function to_int(x: int32): int
axiom bounded_int32:
  forall x: int32. -2^31 ≤ to_int(x) < 2^31

val int32_add(x: int32, y: int32): int32
  requires -2^31 ≤ to_int(x) + to_int(y) < 2^31
  ensures to_int(result) = to_int(x) + to_int(y)
```

Binary Search with overflow checking

See `bin_search_int32.mlw`

Binary Search with overflow checking

See `bin_search_int32.mlw`

Application

Used for translating mainstream programming language into Why3:

- From C to Why3: Frama-C, Jessie plug-in
  See `bin_search.c`
- From Java to Why3: Krakatoa
- From Ada to Why3: Spark2014

Floating-Point Arithmetic

- Limited range $\Rightarrow$ exceptional behaviors.
- Limited precision $\Rightarrow$ inaccurate results.

Floating-Point Data

IEEE-754 Binary Floating-Point Arithmetic.
Width: $1 + w_e + w_m = 32$, or 64, or 128.
Bias: $2^{w_e - 1} - 1$. Precision: $p = w_m + 1$.

A floating-point datum

sign s	biased exponent e' (w_e bits)	mantissa m (w_m bits)

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A floating-point datum

sign s	biased exponent e' (w_e bits)	mantissa m (w_m bits)

represents

- if $0 < e' < 2^{w_e} - 1$, the real $(-1)^s \cdot \overline{1.m'} \cdot 2^{e'-bias}$, normal
- if $e' = 0$,
  - ± 0 if $m' = 0$, zeros
  - the real $(-1)^s \cdot \overline{0.m'} \cdot 2^{-bias+1}$ otherwise, subnormal
- if $e' = 2^{w_e} - 1$,
  - $(-1)^s \cdot \infty$ if $m' = 0$, infinity
  - *Not-a-Number* otherwise. NaN

Floating-Point Data

$$\begin{array}{ccccc} \boxed{1} & & \boxed{11000110} & & \boxed{10010011110000111000000} \\ s & & e & & f \\ \downarrow & & \downarrow & & \downarrow \\ (-1)^s & \times & 2^{e-B} & \times & 1.f \\ & & & & \\ (-1)^1 & \times & 2^{198-127} & \times & 1.10010011110000111000000_2 \end{array}$$

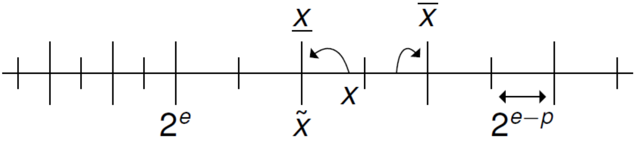
$$-2^{54} \times 206727 \approx -3.7 \times 10^{21}$$

Semantics for the Finite Case

IEEE-754 standard

A floating-point operator shall behave as if it was first computing the infinitely-precise value and then rounding it so that it fits in the destination floating-point format.

Rounding of a real number x:



Overflows are not considered when defining rounding: exponents are supposed to have no upper bound!

Specifications, main ideas

Same as with integers, we specify FP operations
so that no overflow occurs.

```
constant max : real = 0x1.FFFFFEp127
predicate in_float32 (x:real) = abs x ≤ max
type float32
function to_real(x: float32): real
axiom float32_range: forall x: float32. in_float32 (to_real x)

function round32(x: real): real
(* ... axioms about round32 ... *)

function float32_add(x: float32, y: float32): float32
  requires in_float32(round32(to_real x + to_real y))
  ensures to_real result = round32 (to_real x + to_real y)
```

Specifications in practice

- Several possible rounding modes
- many axioms for `round32`, but incomplete anyway
- Specialized prover: Gappa `http://gappa.gforge.inria.fr/`

Demo: `clock_drift.c`

Deductive verification nowadays

More native support in SMT solvers:

- *bitvectors* supported by CVC4, Z3, others
- *theory of floats* supported by Z3, CVC4, MathSAT

Using such a support for deductive program verification remains an open research topic

- Issues when bitvectors/floats are mixed with other features: conversions, arrays, quantification

Fumex et al.(2016) C. Fumex, C. Dross, J. Gerlach, C. Marché. Specification and proof of high-level functional properties of bit-level programs. 8th NASA Formal Methods Symposium, LNCS 9690 Science

Boldo, Marché (2011) S. Boldo, C. Marché. Formal verification of numerical programs: from C annotated programs to mechanical proofs. Mathematics in Computer Science, 5:377–393