Ruby Extension Library Verified using Coq Proof-assistant

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About This Talk

- Formal verification for fast & safe program in C
- Quality assurance other than test

Materials

- Ruby
- Coq
- C
- HTML escape
- Intel SSE

Do you know all of them?

Coq Proof-assistant

- Proof assistant
  - Programmer writes a proof
  - Coq checks the proof
- Coq has ML-like language, Gallina
  - Powerful type system
  - Gallina programs can be proved
- Program Extraction to OCaml, Haskell and Scheme
- C code generation by our plugin
  https://github.com/akr/codegen

Development Flow

1. In Coq
   i. Define a specification and implementation
   ii. Verify them
   iii. Convert the implementation into C
2. In C
   i. Define supplemental code
   ii. Define glue code for Ruby
3. In Ruby
   i. Use the verified implementation

Benefits of Verification

- Correct
- Fast

Compared to:

- C: fast but dangerous
- Ruby: safe but slow

Simple Example: pow

Specification of power function in Gallina:

```
(* pow a k = a ** k *)
Fixpoint pow a k :=
  match k with
  | 0 => 1
  | k'.+1 => a * pow a k'
  end.
```

Good: Obviously correct

Bad: Naive algorithm

Bad: (non-tail) recursion

Complex but Fast pow

```
Definition uphalf' n := n – n./2.
(* fastpow_iter a k x = (a ** k) * x *)
Fixpoint fastpow_iter a k x :=
  if k is k'.+1 then
    if odd k then
      fastpow_iter a k' (a * x)
    else
      fastpow_iter (a * a) (uphalf' k') x
  else
    x.
Definition fastpow a k := fastpow_iter a k 1.
```

Complex and Fast pow (2)

Bad: Not obviously correct

Good: Fast algorithm

Good: Tail recursion

Correctness for fastpow

- We can prove equality of fastpow and pow in Coq

  Lemma fastpow_pow a k : fastpow a k = pow a k.
  Proof. (snip) Qed.

- This is the evidence that fastpow is correct
- The proof is snipped because Coq proof is unreadable
  (interactive environment is required to read proof)

Code Generation from fastpow

```
nat n3_fastpow_iter(nat v2_a, nat v1_k, nat v0_x) {
  n3_fastpow_iter:;
  switch (sw_nat(v1_k)) {
    case_O_nat: { return v0_x; }
    case_S_nat: {
      nat v4_k_ = field0_S_nat(v1_k);
      bool v5_b = n1_odd(v1_k);
      switch (sw_bool(v5_b)) {
      case_true_bool: {
        nat v6_n = n2_muln(v2_a, v0_x);
        v1_k = v4_k_; v0_x = v6_n; goto n3_fastpow_iter; }
      case_false_bool: {
        nat v7_n = n2_muln(v2_a, v2_a);
        nat v8_n = n1_uphalf_(v4_k_);
        v2_a = v7_n; v1_k = v8_n; goto n3_fastpow_iter; }}}}}
nat n2_fastpow(nat v10_a, nat v9_k) {
  nat v11_n = n0_O();
  nat v12_n = n1_S(v11_n);
  return n3_fastpow_iter(v10_a, v9_k, v12_n); }
```

Primitives for fastpow

- Types
  - bool: Boolean
  - nat: Peano's natural number
- Functions
  - odd: nat → bool
  - muln: nat → nat → nat

bool

- Coq definition

```
Inductive bool : Set :=
| true : bool
| false : bool.
```

- C Implementation

```
/* bool type */
#include <stdbool.h>

/* constructors */
#define n0_true() true
#define n0_false() false
```

```
/* macros for "match" */
#define sw_bool(b) (b)
#define case_true_bool default
#define case_false_bool case false
```

nat (Peano's natural number)

- Coq definition

```
Inductive nat : Set :=
| O : nat              (* zero *)
| S : nat → nat.       (* successor function *)
```

- C Implementation

```
typedef uint64_t nat;
#define n0_O() ((nat)0)
#define n1_S(n) ((n)+1)
#define sw_nat(n) (n)
#define case_O_nat case 0
#define case_S_nat default
#define field0_S_nat(n) ((n)-1)
```

```
/* primitive functions */
#define n2_addn(a,b) ((a)+(b))
#define n2_subn(a,b) ((a)-(b))
#define n2_muln(a,b) ((a)*(b))
#define n2_divn(a,b) ((a)/(b))
#define n2_modn(a,b) ((a)%(b))
#define n1_odd(n) ((n)&1)
```

Verified Program Development

- Describe a program in Gallina
- Describe a proposition (Gallina type)
- Describe a proof (Gallina program)
- Coq checks the proof (type check)
- C code generation from the Gallina program
- Define supplemental C code

Curry-Howard Correspondence

They have same structure:

- proposition ~ type
- proof ~ program

"Prove a proposition" =
"Write a program of the correspond type"

Example: A /\ B

- proof
  - A, B : propositions
  - A /\ B : proposition of "A and B".
  - proof for A /\ B : pair of proof for A and proof for B
- program
  - A, B : types
  - A /\ B : pair of A and B
    type AandB = A * B
  - value of A /\ B : pair of value of A and a value of B

Logical Formulae

- Propositional logic
  - and : type AandB = A * B
  - or : type AorB = a of A | b of B
  - imply : type AimplyB = A → B

- Predicate logic (dependent types)
  - ∀x:A. B : A → B
  - ∃x:A. B : pair of x and proof of B
  - x = y : equality

Specification and Correctness

- spec(x) = obviously-correct-function
- imp(x) = complex-function

- proposition of correctness:

  $\forall x.\ imp(x) = spec(x)$

  (Other form of specification is possible...)

Code Generation to C

- C code generation by our plugin
  https://github.com/akr/codegen

- Simple mapping from Gallina subset to C
- Tail recursion is translated to goto
- Fully customizable implementation of data types

What is Verified?

Verified:

- The algorithm of fastpow

Not Verified

- Translation mechanism to C
- Implementation of primitives:
  bool, nat, muln, odd

Not Explained

- Program failures (such as integer overflow)
  It is possible to prove about program failures using our monadification plugin. But we ignore this issue today.

HTML Escape

CGI.escapeHTML substitutes five characters in a string:

& → &

< → <

> → >

" → "

' → '

We ignore non-ASCII characters for simplicity.

HTML Escape Specification

```
Definition html_escape_alist :=
  map (fun p => (p.1, seq_of_str p.2)) [::
  ("&"%char, "amp"); ("<"%char, "lt"); (">"%char, "gt");
  (""""%char, "quot"); ("'"%char, "#39") ].

Definition html_escape_byte c :=
  if assoc c html_escape_alist is Some p then
    "&" ++ p.2 ++ ";"
  else
    [:: c].

Definition html_escape s := flatten (map html_escape_byte s).
```

This seems correct but doesn't work optimal in C: list (seq) and higher order function

Primitive Types for HTML Escape

We need char* for efficiency

Coq		C
bool	→	bool
nat	→	uint64_t
ascii	→	unsigned char
byteptr	→	char*
buffer	→	Ruby's VALUE (String)

ascii type (unsigned char)

- Coq definition

  (* ascii is 8 booleans *)

  Inductive ascii : Set := Ascii (_ _ _ _ _ _ _ _ : bool).

- C Implementation

  typedef unsigned char ascii;

byteptr type (char*)

- Required operations to scan a memory region: advance a pointer, dereference a pointer
- Coq definition
  "char*" is represented using a list of ascii and an index in it.
  Inductive byteptr := bptr : nat → seq ascii → byteptr.
  bptradd (bptr i s) n = bptr (i + n) s
  bptrget (bptr i s) = nth "000"%char s i
- C Implementation

```
typedef const char *byteptr;
#define n2_bptradd(p, n) (p + n)
#define n1_bptrget(p) (*(unsigned char *)p)
```

buffer type (VALUE)

- Required operation for result buffer:
  add data at end of buffer
- Coq definition
  Inductive buffer := bufctr of seq ascii.
  Definition bufaddmem buf ptr n := ...
- C Implementation
  - buffer: VALUE (String)
  - bufaddmem: rb_str_buf_cat
- bufaddmem is pure but rb_str_buf_cat is destructive.
  This problem is solved by copying the string when necessary

Tail Recursive HTML Escape Translatable to C

```
Fixpoint trec_html_escape buf ptr n :=
  match n with
  | 0 => buf
  | n'.+1 =>
      let: (escptr, escn) :=
        html_escape_byte_table (bptrget ptr) in
      trec_html_escape
        (bufaddmem buf escptr escn)
        (bptradd ptr 1)
        n'
  end.
```

Correctness of Tail Recursive HTML Escape

- Definition trec_html_escape_stub s :=
  s_of_buf (trec_html_escape
  (bufctr [::]) (bptr 0 s) (size s)).
- Lemma trec_html_escape_ok s :
  trec_html_escape_stub s = html_escape s.
  Proof. (snip) Qed.

Translated trec_html_escape in C

```
buffer n3_trec_html_escape(buffer v2_buf, byteptr v1_ptr, nat v0_n) {
  n3_trec_html_escape:;
  switch (sw_nat(v0_n)) {
    case_O_nat: { return v2_buf; }
    case_S_nat: {
      nat v4_n_ = field0_S_nat(v0_n);
      ascii v5_a = n1_bptrget(v1_ptr);
      prod_byteptr_nat v6_p = n1_html_escape_byte_table(v5_a);
      byteptr v7_escptr = field0_pair_prod_byteptr_nat(v6_p);
      nat v8_escn = field1_pair_prod_byteptr_nat(v6_p);
      buffer v9_b = n3_bufaddmem(v2_buf, v7_escptr, v8_escn);
      nat v10_n = n0_O();
      nat v11_n = n1_S(v10_n);
      byteptr v12_b = n2_bptradd(v1_ptr, v11_n);
      v2_buf = v9_b;
      v1_ptr = v12_b;
      v0_n = v4_n_;
      goto n3_trec_html_escape; } } }
```

Primitive Type for SSE

- m128 → __m128i
- __m128i is defined by intrinsics for SSE

m128 type

- m128 consists 16 bytes. (SSE register is 128 bits)
- Coq definition

```
 Inductive m128 := c128 :
   ascii → ascii → ascii → ascii → ascii → ascii → ascii → ascii →
   ascii → ascii → ascii → ascii → ascii → ascii → ascii → ascii → m128.
Definition m128_of_seq s := c128
   (nth "000"%char s 0) ...(snip)... (nth "000"%char s 15).
Definition m128_of_bptr ptr :=
   m128_of_seq (drop (i_of_bptr ptr) (s_of_bptr ptr)).
```

- C Implementation

```
 typedef __m128i m128;
 #define n1_m128_of_bptr(p) _mm_loadu_si128((__m128i const*)(p))
```

SSE pcmpestri instruction

- pcmpestri is a SSE4.2 instruction
  Packed Compare Explicit Length Strings, Return Index
- Coq definition

```
Definition cmpestri_ubyte_eqany_ppol_lsig
    (a : m128) (la : nat) (b : m128) (lb : nat) :=
  let sa := take la (seq_of_m128 a) in
  let sb := take lb (seq_of_m128 b) in
  let p := mem sa in
  if has p sb then find p sb else 16.
```

- C Implementation

```
#define n4_cmpestri_ubyte_eqany_ppol_lsig(a, la, b, lb) \
  _mm_cmpestri(a, la, b, lb, \
      _SIDD_UBYTE_OPS|_SIDD_CMP_EQUAL_ANY| \
      _SIDD_POSITIVE_POLARITY|_SIDD_LEAST_SIGNIFICANT)
```

- _mm_cmpestri is SSE intrinsic function which generates pcmpestri.

HTML Escape using SSE

```
Fixpoint sse_html_escape buf ptr m n :=
  match n with
  | 0 => bufaddmem buf ptr m
  | n'.+1 =>
      let p1 := bptradd ptr m in
      if n <= 15 then
        trec_html_escape (bufaddmem buf ptr m) p1 n
      else
        let i := cmpestri_ubyte_eqany_ppol_lsig
            chars_to_escape num_chars_to_escape
            (m128_of_bptr p1) 16 in
        if 16 <= i then
          sse_html_escape buf ptr (m + 16) (n' - 15)
        else
          let buf2 := bufaddmem buf ptr (m + i) in
          let p2 := bptradd ptr (m + i) in
          let c := bptrget p2 in
          let p3 := bptradd p2 1 in
          let: (escptr, escn) := html_escape_byte_table c in
          let buf3 := bufaddmem buf2 escptr escn in
          sse_html_escape buf3 p3 0 (n' - i)
  end.
```

Correctness of HTML Escape using SSE

- Definition sse_html_escape_stub s :=
  s_of_buf (sse_html_escape
   (bufctr [::]) (bptr 0 s) 0 (size s)).
- Lemma sse_html_escape_ok s :
  sse_html_escape_stub s = html_escape s.
  Proof. (snip) Qed.

Glue Code for Ruby Extension

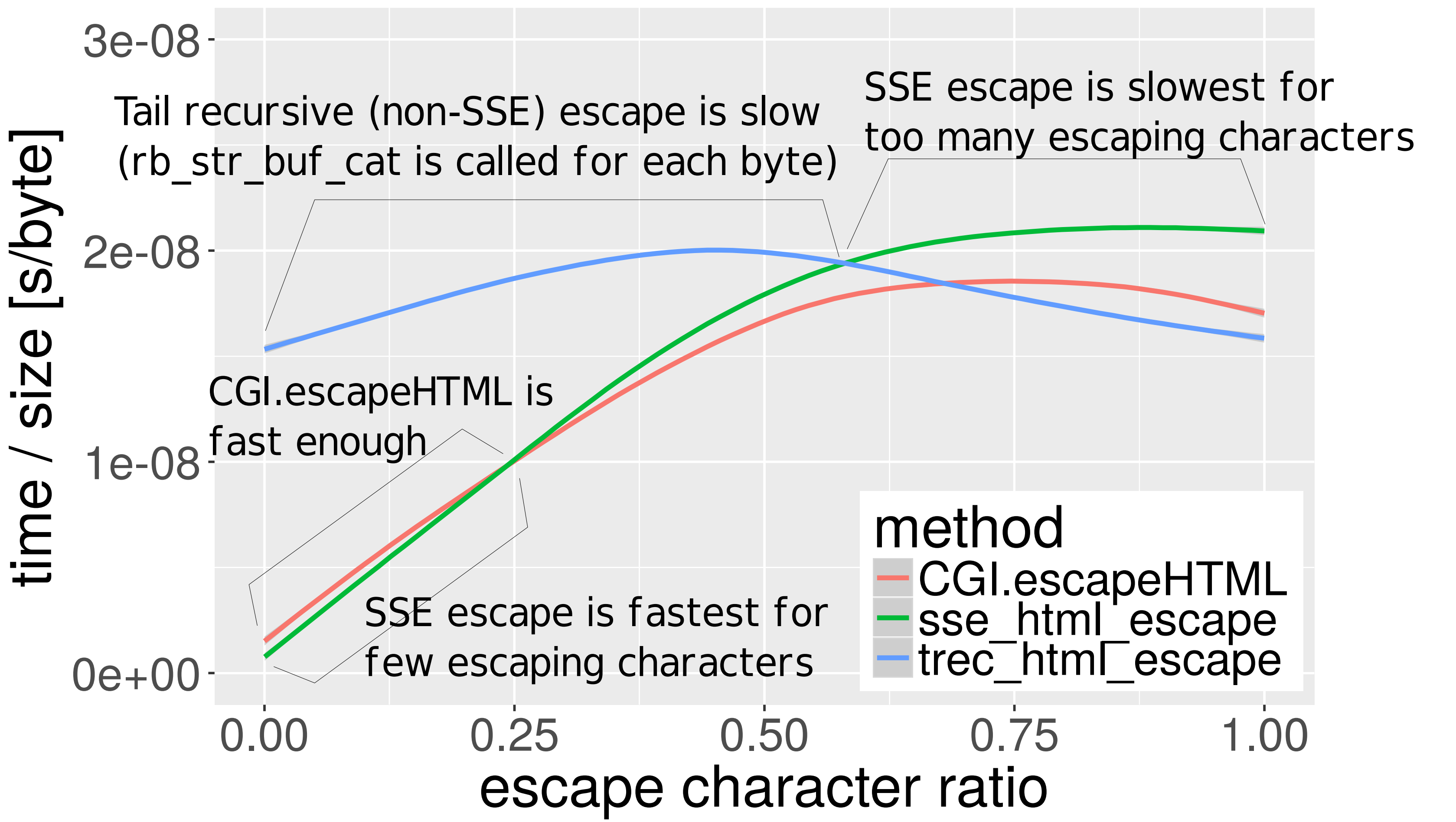
```
VALUE
sse_html_escape(VALUE self, VALUE str)
{
  buffer buf;
  StringValue(str);
  RB_GC_GUARD(str);
  buf = buffer_new(RSTRING_LEN(str));
  n4_sse_html_escape(buf, RSTRING_PTR(str), 0, RSTRING_LEN(str));
  return buf.str;
}

void
Init_verified_html_escape()
{
  rb_define_global_function("sse_html_escape", sse_html_escape, 1);
}
```

Test

```
% ruby -I. -rverified_html_escape \
      -e 'p sse_html_escape("x&y")'
"x&amp;y"
```

Benchmark



Tail recursive (non-SSE) escape is slow
(rb_str_buf_cat is called for each byte)
SSE escape is slowest for
too many escaping characters
CGI.escapeHTML is
fast enough
SSE escape is fastest for
few escaping characters
3e-08
2e-08
1e-08
0e+00
time / size [s/byte]
0.00
0.25
0.50
0.75
1.00
escape character ratio
method
CGI.escapeHTML
sse_html_escape
trec_html_escape

Some Thoughts

- pcmpestrm instruction would be faster than pcmpestri.

Encouragement of Coq

- Realistic programming is possible
- You will learn about "correctness" more precisely

How to write a correct program

Think program's behavior seriously

No tool can support non-thinking person

Think Seriously

Most real programs are too complex to think in a brain

We need an external tool to think the behavior:

- Write the behavior
- Read it and re-thinking

Write the behavior in ...

- Natural language
  - Good: Very flexible
  - Bad: Too flexible, no automatic checking
- Programming language
  - Good: Actually works and testable
  - Bad: Ad-hoc test is very sparse
- Test driven development (TDD)
  - Good: Many examples make us more thinking
  - Bad: Not possible to test all (infinite) inputs
- Formal verification
  - Good: Coq forces us to think correctness for all inputs
  - Bad: Proof is tedious

Importance of learning formal verification

- You will learn how to describe correctness very preciously.
- As you learned how to describe behavior very preciously by learning programming

Summary

- Correct and fast C function can be generated from Coq
- The function is usable from Ruby
- Encourage Coq to learn about correctness

Extra Slides

Benchmark Script

```
require 'cgi'
require 'verified_html_escape'
methods = %w[sse_html_escape trec_html_escape CGI.escapeHTML]
puts "size[byte],method,esc_ratio,time[s]"
max_size = 40000
num_sizes = 200
num_ratios = 50
code = []
methods.each {|meth|
  num_sizes.times {
    num_ratios.times {
      sz = 1+rand(max_size-1)
      esc_ratio = rand
      code << <<~End
        sz = #{sz}
        meth = #{meth.dump}
        esc_ratio = #{esc_ratio}
        num_escape = (sz * esc_ratio).to_i
        src = (['a'] * (sz - num_escape) + ['&'] * num_escape).shuffle.join
        GC.disable
        t1 = Process.clock_gettime(Process::CLOCK_THREAD_CPUTIME_ID)
        dst = #{meth}(src)
        t2 = Process.clock_gettime(Process::CLOCK_THREAD_CPUTIME_ID)
        GC.enable
        t = t2-t1
        puts "\#{sz},\#{meth},\#{esc_ratio},\#{t}"
      End
    }
  }
}
eval code.shuffle.join
```