Bidirectional and executable specifications of machine code decoding and encoding

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Machine Code Decoding/Encoding

- Binary code analysis and transformation
  - Analyze binary code for security, for verification, …
  - Binary rewriting: e.g. insert more instructions into the program for security, for automatic parallelization, ….
- Require machine code decoding
  - From bits to abstract syntax of machine instructions
- Also require machine code encoding
  - From abstract syntax of machine instructions to bits

Decoder Specification Language

- Part of RockSalt work (PLDI 2012)
- Formally encoded in Coq
- Type-indexed parsing combinators for regular grammars
  - Regular grammars: regular expressions + semantic actions
  - Allow transliteration of decoding tables to declarative grammars
  - Then automatically generate executable decoders from grammars, with correctness proofs in Coq

Example Grammar for INC in x86

INC – Increment by 1	
reg	1111 111w : 11 000 reg
reg (alternate encoding)	0100 0 reg
memory	1111 111w : mod 000 r/m

Decode pattern

```
Definition INC_g : grammar instr :=
   "1111111" $$ bit $ "11000" $$ reg
   @ (fun (width,r) => INC width (Reg_op r))
|| "0100" $$ "0" $$ reg
   @ (fun r => INC true (Reg_op r
|| "1111" $$ "111" $$ bit $ (emodrm "000")
   @ (fun (w,op1) => INC w op1).
```

Semantic action

Alternatives

Regular Grammar DSL

Indexed by the type of semantic values returned by the grammar

```
Inductive grammar : Type -> Type :=
| Char : char -> grammar char
| Eps : grammar unit
| Zero : ∀T, grammar T
| Cat : ∀T U, grammar T -> grammar U -> grammar (T*U)
| Alt : ∀T U, grammar T -> grammar U -> grammar (T+U)
| Map : ∀T U, grammar T -> (T -> U) -> grammar U
| Star : ∀T, grammar T -> grammar (list T)
```

Concatenation: return a pair

Alternation: return a tagged union

Map: apply a semantic action

```
Infix "+" := Alt.
Infix "$" := Cat.
Infix "@" := Map.
g1 || g2 := (g1 + g2) @
  (fun v => match v with inl v1 => v1 | inr v2 => v2)
```

Union: forgetful

Denotational Semantics

```
[[ ]] : grammar T -> (string * T) -> Prop.
[[Eps]] = {(nil, tt)}
[[Zero]] = {}
[[Char c]] = {(c::nil, c)}
[[Alt g1 g2]]={(s,inl v) | (s,v) in [[g1]]} U
             {(s,inr v) | (s,v) in [[g2]]}
[[Cat g1 g2]] =
         {(s1++s2,(v1,v2)) | (si,vi) in [[gi]]}
[[Star g]] = {(nil, nil)} U
         {(s,v) | s≠nil /\
                 s in [[Cat g (Star g)]]}
[[Map g f]] = {(s, f v) | (s,v) in [[g]]}
```

From Grammars to Parsers

- An operational semantics (interpreter)
  - Derivative-based parsing: old idea due to Brzozowski (1964), revitalized by Reppy et al., and extended by Might
  - Proven correct in Coq w.r.t the denotational semantics
- A parser generator (compiler)
  - Compile to DFA tables with semantic actions
  - Also proven correct in Coq and with termination proofs
- Parser correctness:
  `(s,v) ∈ [[g]] iff parse g s = Some v`

What about the Encoder?

- Natural idea: have a **bidirectional grammar** for both decoding and encoding at the same time
  - Derive a decoder and an encoder from the bigrammar
- Benefits
  - Decoder and encoder spec can share parts
  - Can relate the derived decoder and encoder using some "round-trip" theorem

Relating Parsing and Pretty Printing

- Parser: from input strings to semantic values
- Pretty printer: from semantic values to input strings
- Ideally, a parser and its reverse pretty printer should form a **bijection**
- However, the requirement is too strong in practice
  - Information loss during parsing
  - Loose semantic domains

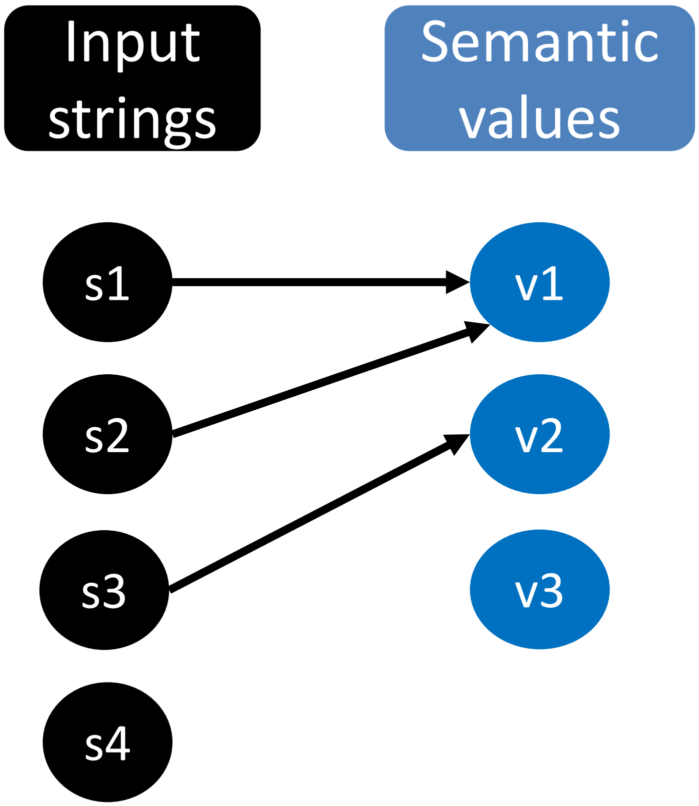
Information Loss During Parsing

- Parsing often loses information
- For example
  - A parser for source code forgets the amount of white spaces
  - In x86 decoding, multiple bit encoding for the same instruction
- As a result
  - Multiple input strings may be parsed to the same semantic value
  - When inverting such a semantic value, the pretty printer has to choose a specific input string (or list all possible ones)

Loose Semantic Domains

- For uniformity the semantic domain of a parser may include values that cannot be possible parsing results
- An example:
  - x86 instructions takes zero or more operands
  - An operand can be a memory operand, an immediate operand, or a register operand
  - But for a specific instruction, certain combinations of operands are not possible
- Some of these cases could be fixed by introducing tighter domains
  - But in general would make abstract syntax messy
- As a result
  - Pretty printing is partial: cannot invert some semantic values

Relating Input and Output Domains



- Multiple input strings can be parsed to the same semantic value
- Some semantic values may not be possible parsing results
- Parsing is also partial and may reject some input strings

Consistency Properties

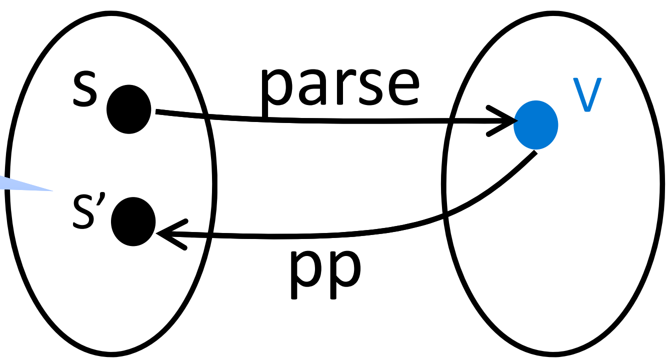
- parse: ∀T, (bigrammar T) −> list char −> option T

  pretty-print: ∀T, (bigrammar T)−> T −> option (list char)

- **Consistency property 1**

  If parse g s = Some v, then exists s' so that pretty-print g v = Some s'.

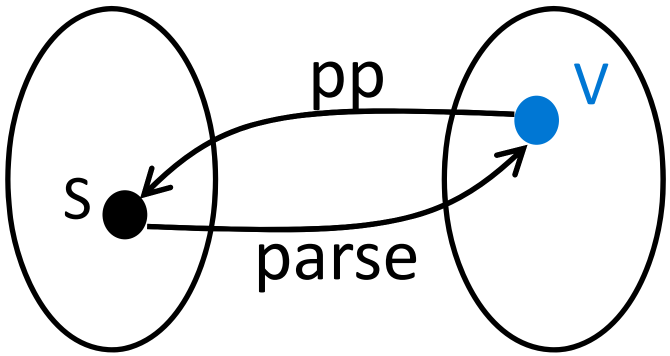
s' may be different from s



Consistency Properties

- **Consistency property 2**

If pretty-print g v = Some s, then parse g s = Some v



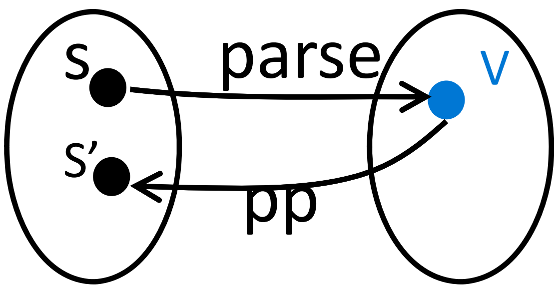
Note: it places no obligation when the pretty printer cannot invert v

Some Related Work

- Haskell community: invertible syntax for both parsing and pretty printing
  - Jansson & Jeuring [ESOP 99]; Alimarine et al. [Haskell 05]; Rendel & Ostermann [Haskell 10]
- Our work is embedded in Coq, with machine-checked correctness proofs

Consistency Properties In Related Work

- Jansson & Jeuring and Alimarine et al. require bijections; too strong
- Rendel & Ostermann require **partial isomorphisms**



  - Specify an **explicit equivalence relation** and require s and s' in the equivalence relation in Prop 1
- Our approach uses an implicit equivalence relation: all input strings that are parsed to the same semantic value are considered equivalent

A Bigrammar DSL

```
Inductive bigrammar : Type -> Type :=
| Char : char -> bigrammar c
| …
| Star : ∀T, bigrammar T -> bigrammar (list T)
| Map: ∀T U, (f1: T -> U) (f2: U -> option T)
       (g: bigrammar T)(pf: invertible(f1, f2, g)),
        bigrammar U
```

Map function

Reverse function

f1 and f2 are invertible

- Constructors other than Map are reversible and exactly the same as the previous decoder grammar DSL
- Invertible def derived from the consistency properties

Pretty Printer

```
pretty-print (Char c) =
  λc0. if c=c0 then Some [c] else None

pretty-print (Alt g1 g2) =
  λ v. match v with
      | inl v1 => pretty-print g1 v1
      | inr v2 => pretty-print g2 v2 end

pretty-print (Map f1 f2 g pf) =
  λ v. v0 <- f2 v; pretty-print g v0
…
```

Pretty Printer Correctness

- `(1)If (s,v) ∈ [[g]], then exists s’ so that pretty-print g v = Some s’`

  `(2)If pretty-print g v = Some s, then (s,v) ∈[[g]]`

- Consistency properties follow from parser and pretty printer correctness

Engineering a Bigrammar for x86 Decoding and Encoding

- Previously
  - Developed a decoder grammar for x86
  - Manually wrote an encoder (not grammar driven)
- Retrofitted the decoder grammar to get a bigrammar
- Unfortunately, had to change many places in the grammar
  - To make it easier to develop invertibility proofs
  - To make the pretty printer more efficient

Overcoming Engineering Challenges

- Eliminating the use of union operators
  - The use of union results in runtime tests; inefficient
  - Use disjoint sums (tagged unions)
- Reducing proof-checking time
  - First version took hours to finish proof checking
  - Special Coq tactics and dependent types to speed up proof checking
- Tightening semantic domains
  - In the old decoder grammar, many map functions are not surjective, causing **loose semantic domains**
  - Resulting in runtime tests in the encoder
  - We fixed some of those by having tightened semantic domains
- …

x86 and MIPS Bigrammars

	Lines of Coq code
x86 Decoder Grammar	2,194
x86 Encoder (Manually Written)	2,891
x86 Decoder/Encoder Bigrammar	7,254

	Lines of Coq code
MIPS Decoder Grammar	342
MIPS Decoder/Encoder Bigrammar	1,036

- Extracted OCaml code for x86/MIPS decoding and encoding bigrammars

Speed Comparison: Encoder Generated from the Bigrammar vs. the Manually Developed Encoder

	Size	Instr count	Bigrammar encoder	Manual encoder
tailf	14KB	2,020	1.19s	2.05s
pwd	26KB	3,938	2.50s	4.19s
cat	46KB	7,458	4.99s	8.28s
ls	103KB	18,377	10.73s	18.92s

- Manual encoder used many literal strings during encoding, resulting in higher memory consumption
  - 70% more memory than the bigrammar encoder

More Info in Papers

- Decoder specification language
  - RockSalt [PLDI 2012]
  - Used the x86 decoder for proving the correctness of a machine code verifier
- Bidirectional decoder/encoder language
  - Conference version [VSTTE 2016]
  - Journal version: [Journal of Automated Reasoning 2017]

Future Work: Beyond Regular Grammars

- Parsing (and pretty-printing) are security critical
  - Windows: hundreds of parsers for different file formats; many security-critical bugs were found [GoDefRoiD et al. CACM 2012]
- Beyond regular grammars (dependent grammars, CFG, PEG)
  - [Barthwal and Norrish 09]: verified SLR parsing
  - [Jourdan, Pottier, and Leroy 12]: translation validation for LR(1) parsing

The End

- The bigrammar development in Coq can be found at

https://github.com/gangtan/CPUmodels

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More Related Work

- SLED [Ramsey and Fernandez 97]
  - Allows bigrammars for de-/encoding; but no formal consistency requirements and proofs
- Bidirectional XML parsing
  - [Brabrand *et al.* 05]; biXid [Kawanaka and Hosoya 06]
- Pickling/unpickling [Kennedy 04]
- Boomerang: bidirectional lenses
  - [Bohannon *et al.* 08]
  - Modelling the view-update problem in DBs; the reverse direction different from pretty printing

Engineering a Bigrammar for x86-32 Decoding and Encoding

- Retrofitted a previously developed decoder grammar to get a bigrammar
- Unfortunately, had to change many places in the grammar
  - To make it easier to develop invertibility proofs
  - To make the pretty printer more efficient
- We next discuss some examples

Tightening Semantic Domains

- In the old decoder grammar, many map functions are not surjective, causing **loose semantic domains**
- Some of these can be fixed by having tightened semantic domains

Example: Parsing 32- or 16-Bit Immediates

Reverse function:

```
fun op => match op with
          | Imm_op w => Some w
          | _ => None
        end
```

```
Definition imm_p (op
 grammar operand_t :
  match opsize_override with
   | false => word @ (fun w => Imm_op w)
   | true =>  halfword @
       (fun w => Imm_op (sign_extend16_32 w))
  end.
```

- Two reverse functions; one for each case
- It produces operands; however, the operand domain contains not just immediate operands
- So reverse functions have to do runtime tests

The Fix

- Producing 32-bit immediates instead; clients of the bigrammar applies Imm_op in their map functions when necessary

```
Definition imm_b (opsize_override:bool):
  bigrammar word_t :=
  match opsize_override with
   | false => word
   | true => halfword @
             (fun w => sign_extend16_32 w)
             & (fun w => …)
             & _
  end.
```

The Use of the Union

```
Definition INC_g : grammar instr :=
   "1111" $$ "111" $$ bit $ "11000" $$ reg
   @ (fun (w,r) => INC w (Reg_op r))
|| "0100" $$ "0" $$ reg
   @ (fun r => INC true (Reg_op r)
|| "1111" $$ "111" $$ bit $ (emodrm "000")
   @ (fun (w,op1) => INC w op1).
```

- One inefficient way to a bigrammar
  - Add three reverse functions for the three maps
  - For the first one, pattern match the two arguments; if they are of the form "(w, (Reg_op r)", return Some (w,r); otherwise, return None.
  - A special union bigrammar constructor: try each case and see which one succeeds (returns some value)

Eliminating the Use Of Union

- Use disjoin sums (Alt) to combine cases to get a parse tree

```
  "1111" $$ "111" $$ anybit $ "11000" $$ reg
+ "0100" $$ "0" $$ reg
+ "1111" $$ "111" $$ anybit $ ext_op_modrm_noreg "000"
```

- A single map function from parse trees to instruction arguments
- A single reverse function from arguments to parse trees
- Use tactics to automate the process of generating map and reverse functions as well as the invertibility proof