Narcissus: Correct-By-Construction Derivation of Decoders and Encoders from Binary Formats

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Abstract
It is a neat result from functional programming that libraries of parser combinators can support rapid construction of decoders for quite a range of formats. With a little more work, the same combinator program can denote both a decoder and an encoder. Unfortunately, the real world is full of gnarly formats, as with the packet formats that make up the standard Internet protocol stack. Most past parser-combinator approaches cannot handle these formats, and the few exceptions require redundancy – one part of the natural grammar needs to be hand-translated into hints in multiple parts of a parser program. We show how to recover very natural and nonredundant format specifications, covering all popular network packet formats and generating both decoders and encoders automatically. The catch is that we use the Coq proof assistant to derive both kinds of artifacts using tactics, automatically, in a way that guarantees that they form inverses of each other. We used our approach to reimplement packet processing for a full Internet protocol stack, inserting our replacement into the OCaml-based MirageOS unikernel, resulting in minimal performance degradation.

1 Introduction
Decoders and encoders are vital components of any software that communicates with the outside world, and accordingly functions that process untrusted data represent a key attack surface for malicious actors. Failures to produce or interpret standard formats routinely result in data loss, privacy violations, and service outages in deployed systems [1–3]. In the case of formally verified systems, bugs in encoder and decoder functions that live in the unverified, trusted code have been shown to invalidate the entire assurance case [20]. There are no shortage of code-generation frameworks [7–9, 17–19, 24, 30, 35, 36, 41, 45] that aim to reduce opportunities for user error in writing encoders and decoders, but these systems are quite tricky to get right and have themselves been sources of serious security bugs [4].

Combinator libraries are an alternative approach to the rapid development of parsers, and they have proven particularly popular in the functional-programming community [28]. This approach has been adapted to generate both parsers and pretty printers from single programs [26, 38]. Unfortunately, combinator libraries suffer from the same potential for bugs as code-generation frameworks, with the additional possibility for users to introduce errors when extending the library with new combinators. In this paper, we present Narcissus, a combinator-style framework for the Coq proof assistant that eliminates the possibility of such bugs, enabling the derivation of encoders and decoders that are correct by construction. Each derived encoder and decoder is backed by a machine-checked functional-correctness proof, and Narcissus leverages Coq’s proof automation to help automate both the construction of encoders and decoders and their correctness proofs. Key to our approach is how it threads information through a derivation, in order to generate decoders and encoders for the sorts of non-context-free languages that often appear in standard networking protocols. We begin by introducing the key features of Narcissus with a series of increasingly complex examples, leading to a hypothetical format of packets sent by a temperature sensor to a smart home controller. In order to build up the reader’s intuition, we deliberately delay a discussion of the full details of Narcissus until Section 2. The code accompanying our tour is included in our code supplement in the src/Narcissus/Examples/README.v file.

1.1 A Tour of Narcissus
Getting started
Our first format is extremely simple:

1: User input

Record sensor_msg :=
{ stationID: word 8; data: word 16 }.

Let format := format_word ◦ stationID ++ format_word ◦ data.

Let invariant (msg: sensor_msg) := ⊤.

Let enc_dec: EncoderDecoderPair format invariant :=
ltac:(derive_encoder_decoder_pair).

2: Encoder

Let encode := encoder_impl enc_dec.
stationID >> SetCurrentByte >>
data >> (high_bits 8 >> SetCurrentByte >>
low_bits 8 >> SetCurrentByte)

3: Decoder

Let decode := decoder_impl enc_dec.
b ← GetCurrentByte;
The encoder uses the \( \gg \) (both implicit) and returns the encoded packet, or invariant 

\[
\text{Let } \text{decode} := \text{decoder_impl enc_dec}.
\]

\[
\text{Let } \text{encode} := \text{encoder_impl enc_dec}.
\]

\[
\text{Let } \text{enc_dec}: \text{EncoderDecoderPair format invariant :=}
\]

\[
\text{Let invariant } (\text{msg}: \text{sensor_msg}) := \top.
\]

\[
\text{Let format :=}
\]

\[
\text{after on a 16-bit boundary, we introduce 8 bits of padding logic.}
\]

\[
\text{this byte-alignment transformation is part of the derive_encoder_decoder_pair tactic is part of the framework and automatically generates encoder and decoder functions, as well as proofs that they are correct.}
\]

All user input is contained in box 1. sensor_msg is a record type with two fields; the Coq Record command defines accessor functions for these two fields. format specifies how instances of this record are serialized using two format combinators: format_word is a Narcissus primitive that serializes a word bit-by-bit, and ++ is a sequencing operator (write this, then that). invariant specifies additional constraints on well-formed packets; this example does not have any. The derive_encoder_decoder_pair tactic is part of the framework and automatically generates encoder and decoder functions, as well as proofs that they are correct.

Boxes 2 and 3 show the generated code. In box 2, the encoder operates on a data value and a fixed-size byte buffer (both explicit) and returns the encoded packet, or None if it did not fit in the supplied buffer. In box 3, the decoder takes a buffer and returns a packet, or None if the buffer did not contain a valid encoding. Both generated programs live in stateful error monads (\( \leftarrow \) and \( \gg \)) are the usual binding and sequencing operators, offering primitives to read and write a single byte (\( \text{GetCurrentByte, SetCurrentByte} \)).

The encoder uses the \( \gg \) reverse-composition operator (a \( \gg \) \( b \equiv b \circ a \)) to pass record fields to \( \text{SetCurrentByte} \). Since data is 16 bits long, the encoder also uses high_bits and low_bits to extract the first and last 8 bits, and the decoder reassembles them using the \( \cdot \) concatenation operator: this byte-alignment transformation is part of the derive_encoder_decoder_pair logic.

Underspecification We now consider a twist: to align data on a 16-bit boundary, we introduce 8 bits of padding after stationID; these bits will be reserved for future use:

```
Record sensor_msg :=
  ( stationID: word 8; data: word 16 ).
```

```
Let format :=
  format_word \circ stationID
++ format_unused_word 8
++ format_word \circ data.

Let invariant (msg: sensor_msg) := T.

Let enc_dec: EncoderDecoderPair format invariant :=
  ltac:(derive_encoder_decoder_pair).
```

```
Let encode := encoder_impl enc_dec.

stationID \gg SetCurrentByte \gg
const \text{00000000} \gg SetCurrentByte \gg
const \text{00000011} \gg SetCurrentByte \gg
const \text{00110010} \gg SetCurrentByte \gg
(A r \Rightarrow (Vector.nth [0b00; 0b01] \circ fst \circ data) r \cdot (snd \circ data) r)
\gg (high_bits 8 \gg SetCurrentByte \gg
low_bits 8 \gg SetCurrentByte)
```

```
Let decode := decoder_impl enc_dec.

b :: GetCurrentByte;
_ :: GetCurrentByte;
b' :: GetCurrentByte;

w :: \text{ret } b \cdot b';
```

ret \{ ! stationID := b; data := w ! \}

These 8 unspecified bits introduce an asymmetry: the encoder always writes 0x00, but the decoder accepts any value. The lax behavior is crucial because the format_unused_word specification allows conforming encoders to output any 8-bit value; as a result, a correct decoder should accept all 8-bit values. In that sense, the encoder and decoder that Narcissus generates are not strict inverses of each other: the encoder is one among many functions permitted by the formatting specification, and the decoder is the inverse of the entire family described by the format, accepting packets serialized by any conforming encoder.

Constants and enums Our next enhancements are to add a version number to our format and to tag each measurement with a kind, "TEMP" or "HUMIDITY". To save space, we allocate 2 bits for the tag and 14 bits for the measurement:

```
Let kind := EnumType ["TEMP"; "HUMIDITY"].
```

```
Record sensor_msg :=
  { stationID: word 8; data: (kind * word 14) }.
```

```
Let format :=
  format_word \circ stationID
++ format_unused_word 8
++ format_const \text{0b00001111100010}
++ format_enum [0b00; 0b01] \circ fst \circ data
++ format_word \circ snd \circ data.
```

```
Let invariant (msg: sensor_msg) := T.

Let enc_dec: EncoderDecoderPair format invariant :=
  ltac:(derive_encoder_decoder_pair).
```

```
Let encode := encoder_impl enc_dec.

stationID \gg SetCurrentByte \gg
const \text{0b0000000} \gg SetCurrentByte \gg
const \text{0b0000011} \gg SetCurrentByte \gg
const \text{0b11100010} \gg SetCurrentByte \gg
(A r \Rightarrow (Vector.nth [0b00; 0b01] \circ fst \circ data) r \cdot (snd \circ data) r)
\gg (high_bits 8 \gg SetCurrentByte \gg
low_bits 8 \gg SetCurrentByte)
```

```
Let decode := decoder_impl enc_dec.

b :: GetCurrentByte;
_ :: GetCurrentByte;
b' :: GetCurrentByte;

w :: \text{ret } b \cdot b';
```

(if \text{weq w} \text{0b00000111100010} \text{then}
  \begin{align*}
  b & \leftarrow \text{GetCurrentByte}; \\
  b' & \leftarrow \text{GetCurrentByte}; \\
  w & \leftarrow \text{ret } b \cdot b';
  \end{align*}

match index (\text{high_bits 2 w}) [0b00; 0b01] with
  \begin{align*}
  \text{Some } a' & \Rightarrow \text{ret } \{ \text{stationID := b; data := w !} \}
  \end{align*}
  \] 
  | \text{None} \Rightarrow \text{fail end}

The use of format_const in the specification forces conforming encoders to write out the value 0x7e2, encoded over 16 bits. Any input that does not contain that exact sequence is
malformed, which the generated decoder signals by throwing an exception. The argument passed to `format_enum` specifies which bit patterns to use to represent each tag (0b00 for "TEMP", 0b01 for "HUMIDITY"), and the decoder uses this mapping to reconstruct the appropriate enum member.

**Lists and dependencies** Our penultimate example illustrates data dependencies and input restrictions. To do so, we replace our single data point with a list of measurements (for conciseness, we remove tags and use 16-bit words). The `format_list` combinator, to encode a value, simply applies its argument combinator in sequence to each element of a list. We start a derivation as before, but we quickly run into an issue:

\[ \text{Let invariant (msg: sensor_msg) := } \top \]

... 

**User-defined formats** Our final example illustrates a key benefit of the combinator-based approach: integration of user-defined formats and decoders. The advantage here is that Narcissus does not sacrifice correctness for extensibility: every derived function must be correct. This example uses a custom type for sensor readings, readings. To integrate this type into Narcissus, the user also supplies the format specification for this type, corresponding encoders and decoders and proofs of their correctness, and a set of tactics explaining how to integrate this record into a derivation. Section 3 provides the complete details on these ingredients, but for now we note that the `format_reading` specification is nothing more exotic than a nondeterministic function in the style of the Fiat framework [15], and that `enc_readingCorrect` and `dec_readingCorrect` are simply normal Coq proofs.

**Inductive reading :=**

| Temperature (_ : word 14) | Humidity (_ : word 14). |

**Let encode :=**

```coq
Let encode := encoder_impl enc_dec.
```

... 

**Let decode :=**

```coq
Let decode := decoder_impl dec_reading.
```

...
Wrapping up To recap: in Narcissus, users specify formats using a library of combinators. Correct-by-construction encoder and decoder functions are automatically derived from these specifications. Formats may be underspecified, in that a particular source value may be serialized in different ways. Formats may induce dependencies between subformats; the derivation procedure is responsible for tracking these dependencies when generating a decoder. Finally, a user can extend Narcissus with new formats and datatypes by providing a few simple ingredients; extensions are guaranteed not to compromise the correctness of derived functions.

We pause briefly here to contrast the design choices made by Narcissus with other approaches to serializing and deserializeing values, with a fuller discussion deferred to Section 5. There has been a particular focus on formally verifying parsers and pretty printers for programming-language ASTs as parts of compiler frontends [10, 25, 27] or to carry out binary analysis [33, 43]. One of the target applications of Narcissus is formally verified distributed systems, and the restriction to context-free languages (as found in those tools) disallows many of the standard network formats such applications require.

Narcissus has a similar motivation to bidirectional programming languages [12, 34] in which programs can be run “in reverse” to map target values to the source values that produced them. The bidirectional programming language Boomerang adopts a similar combinator-based approach to deriving transformations between target and source values. Invertibility is an intrinsic property of these bidirectional languages, so new combinators require extensions to its metatheory. In contrast, proofs of correctness are built alongside functions in Narcissus, allowing users to augment the framework safely by including a proof justifying a particular implementation strategy as part of an extension.

We now back up and present the complete details of Narcissus in a more bottom-up fashion, before proceeding into evaluation and more comparison with related work. The pieces described below are contained in our code supplement, which may be helpful to consult while reading.

2 Narcissus, Formally

We begin our ground-up explanation of Narcissus with the definition of the formats that capture relationships between structured source values and their serialized representations. The signature of a format from source type S to target type T is defined by a type alias:

\[
\text{FormatM } S \times T \times \Sigma := \text{Set of } (S \times \Sigma \times T \times \Sigma)
\]

That is, a format is a quaternary relation on source values, initial states, target values, and final states. Including states in the format allows us to specify a rich set of formats, including DNS packets. As hinted at by the M suffix, FormatM can be interpreted as the composition of the nondeterminism and stateful monads.

The format combinators showcased in Section 1.1 have straightforward definitions using standard set operations. The \(++\) combinator sequences its subformats using a monoid operation \(\cdot\) provided by its target type.

\[
\begin{align*}
\text{let } \text{invariant } (\text{msg: sensor_msg}) :=
\text{let } \text{enc_dec: EncoderDecoderPair format invariant :=}
\end{align*}
\]

\[
\begin{align*}
&\text{let } \text{ltac:(derive_encoder_decoder_pair).}
\end{align*}
\]

\[
\begin{align*}
&\text{++ formatNat 8 \circ length \circ data}
\end{align*}
\]

\[
\begin{align*}
&\text{++ formatList format_reading \circ data.}
\end{align*}
\]

In addition to enabling users to define their own formats in a familiar monadic style, the nondeterminism monad integrates nicely with Coq’s rewriting machinery when deriving correct encoders. Narcissus includes a library of formats for the standard types listed in Figure 1, most of which have pointed definitions.
### Formats for base types included in Narcissus

| Format               | HO | Format               | HO |
|----------------------|----|----------------------|----|
| Booleans             | no | Fixed-Length Words   | no |
| Peano Numbers        | no | Unspecified BitString| no |
| Variable-Length List | yes| Fixed-Length List    | yes|
| Variable-Length String| no| Fixed-Length String  | no |
| Option Type          | yes| Ascii Character      | no |
| Enumerated Types     | no | Variant Types        | yes|

**Figure 1.** Formats for base types included in Narcissus. HO columns indicate whether the format is higher-order.

We have left the definition of the target type of our formats underspecified until now. Either *bitstrings* or *bytestrings*, i.e., lists of bits or bytes, would be a natural choice, each with its own advantages and disadvantages. Bitstrings have a conceptually cleaner interface but are further away from the buffers used in real systems, while bytestrings are closer to the actual data representation of such buffers but require bit-shifting to enqueue bits one at a time. Narcissus attempts to split the difference by defining $T$ as an abstract data type (ADT). Clients can treat $T$ as a bitstring equipped with operations governed by algebraic laws for monoids and queues, while its actual representation type is closer to that of a bytestring. As mentioned in Section 1.1, our derivation procedure optimizes decoders and encoders to treat this target type as an array of bytes in order to produce more performant implementations.

#### 2.1 Specifying Encoders and Decoders

These relational formats are not particularly useful by themselves—even checking whether a format permits two specific source and target values may be undecidable. Rather, they help to specify the correctness of both encoders and decoders, as we will now see. So far, we have seen examples of relational formats that permit one or many target representations of a particular source value, but in their full generality, there might not be any valid encodings of some source value. As an extreme example, consider the following use of the $\land$ combinator to define an empty relation: $[s \mid \text{False}] \land \text{format\_word}$.

More realistically, our format for Domain Names disallows strings with runs of "\”, e.g., "www.foo.bar.com". To account for formats that exclude some source values, Narcissus encoders are partial functions from source to target values: $\text{EncodeM} : S \times T \times \Sigma \rightarrow S \rightarrow \Sigma \rightarrow \text{Option}(T \times \Sigma)$. Intuitively, a format describes a family of permissible encoders, where each must commit to a single target representation for each source value in the relation. More formally:

**Definition 2.1 (Encoder Correctness).** A correct encoder for a format $\text{format} : \text{FormatM} : S \times T \times \Sigma$ is a partial function, $\text{encode} : \text{EncodeM} : S \times T \times \Sigma$, that only produces encodings of source values included in the format and only produces an error on source values not included in the format:

\[
\forall s \in S \land t \in T \land \sigma \in \Sigma. \text{encode } s \sigma = \text{Some} \left(t, \sigma'\right) \rightarrow (s, \sigma, t, \sigma') \in \text{format} \\
\land \forall s \in S \land t \in T \land \sigma \in \Sigma. \text{encode } s \sigma = \bot \rightarrow \forall \sigma'. \left(s, \sigma, t', \sigma'\right) \notin \text{format}. 
\]

In other words, a valid encoder $\text{encode}$ for a format format $\text{refines}$ format; we henceforth use the notation $\text{encode} \subseteq \text{format}$ to denote that $\text{encode}$ is a correct encoder for format.

Before stating the corresponding definitions for decoders, consider the high-level properties outlined in Section 1.1. Clearly, a correct decoder $\text{decode}$ for a format format must be a left inverse of the relation. That is, $\text{decode}$ must map every element $t$ in the image of $s$ in format back to $s$: $\forall s \in T \rightarrow \{t \mid (s, t) \in \text{format} \rightarrow \text{decode}(t) = s\}$. Less clear is what decode should do with target values that fall outside the image of format: should decode fail on such inputs, or should its behavior be unconstrained in these cases? Our intention is for these decoders to be integrated into other formally verified systems, which will undoubtedly process decoded data further. In order to provide the strongest assurance about the data to downstream functions, Narcissus takes the former approach to malformed and potentially malicious target values, requiring that a correct decoder signal an error when applied to a target value not included in the relation: $\forall s \in T \rightarrow \text{decode}(t) \neq \text{Some} \rightarrow (s, t) \in \text{format}$. While the rest of this paper focuses on deriving decoders satisfying both criteria, our approach also straightforwardly applies to the derivation of decoders only satisfying the first criterion, in the case that users choose to sacrifice strict format validation for efficiency, e.g., by not checking checksums. However, we also note that there are compelling security reasons to enforce determinism (e.g., by forcing return of a distinct error value on malformed inputs), to cut off potential side channels via demonic choice between legal alternatives. (E.g., consider a decoder integrated within an e-mail server, which decodes malformed packets into the contents of other users’ inboxes.)

Looking at the signature of decoders in Narcissus,

\[
\text{DecodeM} : S \times T \times \Sigma \rightarrow T \rightarrow \Sigma \rightarrow \text{Option}(S \times \Sigma) 
\]

we see we need to adapt these notions of correctness to account for the state used by a decoder. Whereas an encoder is a refinement of a format, and thus used identical types of state, we do not force compatible decoders and formats to share the same type of state. To see why, consider a simplified version of the format for DNS domain names [32], which keeps track of the locations of previously formatted domains via its state argument:

\[
\text{Let } \text{format\_domain} : (d : \text{domain}) (\sigma : \text{domain} \rightarrow \text{word}) := \text{format\_domain} \cup \text{format\_word} (\sigma \circ \text{domain}) 
\]

This example uses an optional compression strategy in which a domain name can either be serialized or replaced with a pointer to the location of a previously formatted occurrence. A decoder for domains should also keep track of this information, in order to decode pointers:

\[
\text{Let } \text{decode\_domain} : (t : T) (\sigma : \text{word} \rightarrow \text{domain}) := ... 
\]

In order for $\text{decode\_domain}$ to be correct, its state needs to “agree” with the state used to format it input.
tion of decoder correctness captures agreement via a binary relation representing when format and decoder states are consistent. Hence our full notion of decoder correctness, one that accounts for both state and erroneous target values.

**Definition 2.2 (Decoder Correctness).** A correct decoder for a format, \( \text{format} \) \( \subseteq \) \( \Sigma \), and relation on states, \( \approx \) \( \subseteq \) \( \Sigma E \times \Sigma D \), is a function, \( \text{decode} : \text{DecodeM} S T \Sigma D \), that, when applied to a valid target value and initial state, produces a source value and final state similar to one included in format, signaling an error otherwise:

\[
\forall (s_E, \sigma_E) : \Sigma E \exists (s_D, \sigma_D) : \Sigma D \exists t : T. (s, \sigma_E, t, \sigma_E') \in \text{format} \land \sigma_E \approx \sigma_D \rightarrow \exists \sigma_D', \text{decode} t \sigma_D = \text{Some} (s, \sigma_D') \land \sigma_E' \approx \sigma_D', \\
(\exists \sigma_D', \text{decode} t \sigma_D = \text{Some} (s, \sigma_D') \land \sigma_E' \approx \sigma_D', \\
\forall (s_E, \sigma_E) : \Sigma E \exists (s_D, \sigma_D) : \Sigma D \exists t : T. (s, \sigma_E, t, \sigma_E') \in \text{format} \land \sigma_E' \approx \sigma_D',)
\]

We denote that \( \text{decode} \) is a correct decoder for format under a similarity relation \( \approx \) as format \( \models \text{decode} \).

By definition, it is impossible to find a correct decoder for a non-injective format. While decoders and encoders have independent specifications of correctness, using a common format provides a logical glue that connects the two. We can, in fact, prove the expected round-trip properties between a correct encoder and correct decoder for a common format:

**Theorem 2.3 (Decode Inverts Encode).** Given a correct decoder format \( \models \text{decode} \) and correct encoder \( \text{encode} \) \( \subseteq \) \( \text{format} \) for a common format \( \text{format} \), \( \text{decode} \) is an inverse for \( \text{encode} \) when restricted to source values in the format:

\[
\forall s \in \text{format} \exists t, \sigma_E, \sigma_D. \text{encode} s \sigma_E = \text{Some} (t, \sigma_E') \land \sigma_E \approx \sigma_D \rightarrow \exists \sigma_D', \text{decode} t \sigma_D = \text{Some} (s, \sigma_D')
\]

**Theorem 2.4 (Encode Inverts Decode).** Given a correct decoder format \( \models \text{decode} \) and correct encoder \( \text{encode} \) \( \subseteq \) \( \text{format} \) for a common format \( \text{format} \), encode is defined for all decoded source values produced by \( \text{decode} \):

\[
\forall s \exists t, \sigma_D, \sigma_E. \text{decode} t \sigma_D = \text{Some} (s, \sigma_D') \land \sigma_E \approx \sigma_D \rightarrow \exists \sigma_E', \text{encode} s \sigma_E = \text{Some} (t', \sigma_E')
\]

That encode is an inverse of decode for source values with unique encodings is a direct corollary of Theorem 2.4.

### 2.2 Deriving Correct-by-Construction Encoders

Equipped with precise notions of correctness, we can now define Narcissus’s approach to deriving provably correct encoders and decoders. These functions are byte-aligned in a subsequent derivation step, which we discuss in Section 4. We begin with encoders, since they often have similar structure to their corresponding formats. Intuitively, such a derivation is simply the search for a pair of an encoder function encode and a proof term witnessing that it is correct with respect to a format: encode \( \subseteq \) format. Lemmas like \( \text{encode} \) \( \text{readingCorrect} \) are derivation rules for constructing such proof trees. Leveraging this intuition, we can denote these lemmas using standard inference-rule notation:

**Lemma EncA \((h_1 : H_1) \ (h_2 : H_2) \) : CorrectEncoder A T \( \Sigma \) formatA,encodeA \( \equiv \) \( \text{encodeA} \) \( \subseteq \) \( \text{formatA} \) \( (\text{ENCA}) \)

**Figure 2.** Encoder derivation rules.
hole □ at each step of Figure 3 corresponds to the encoder that is built at the next step; recursively filling these in and simplifying the resulting expression with the monad laws yields the expected encoder for enc_data.

![Figure 3. An example encoder derivation.](image)

### 2.3 Deriving Correct-by-Construction Decoders

Before defining similar rules for decoders, we pause to consider how they are used in a derivation. While the top-level decoder we want to derive clearly aligns with our definition of \( \cong \), the decoders for its subformats require a slightly altered definition of correctness. In more detail, consider what the components used in a reusable decoder for \( \cong \) should look like, given a decoder composition operator \( +_D \):

\[
\text{format}_1 + \text{format}_2 \cong \text{decode}_1 +_D \text{decode}_2
\]

The natural way to decode the value resulting from sequencing \( \text{format}_1 \) and \( \text{format}_2 \) is to have \( \text{decode}_1 \) return any unconsumed portion of the target value for \( \text{decode}_2 \) to finish processing. Unfortunately, this convention does not align with our definition of \( \cong \), which expects a decoder to process the target value completely. We can, however, emulate it by extending a format to include an arbitrary "tail" in its source type, which is appended to the end of the original serialized value:

\[
(s, \sigma, t, \sigma') \in \text{format}^+ \leftrightarrow \exists t'. (\text{fst } s, \sigma, t', \sigma') \in \text{format} \land t = t' \land \text{snd } s
\]

Framing our derivation rules in terms of these "partial" formats forces a correct decoder to return the unconsumed portion of the bitstream unchanged:

Let CorrectDecoder (\( ST \in \sigma \in \sigma') \text{ fmt dec } \equiv \text{ fmt}^+ \cong \text{ dec}

The key decoder-derivation rules in NARCISUS are presented in Figure 4, again using an inference-rule-style notation. We emphasize that each of our decoder-derivation rules assumes CorrectDecoder fmt dec for its premises and concludes a similar fact. To see why it is essential that we enforce CorrectDecoder for each intermediate term, consider a simple format for card suits which uses unit for the state type (we elide the trivial state values below):

\[
\text{format}_\text{suit} \equiv \{(\spadesuit, 0b11), (\heartsuit, 0b0), (\diamondsuit, 0b1), (\clubsuit, 0b10)\}
\]

To format a pair of cards, we could format each card in sequence: \( \text{format}_\text{suit} \circ \text{fst} + \text{format}_\text{suit} \circ \text{snd} \). This format is clearly not injective, as there is no way to distinguish between the encodings of \( (\spadesuit, \heartsuit) \) and \( (\diamondsuit, \spadesuit) \). Luckily, we immediately run into a problem if we try to apply DecSeq to derive a decoder for this format. The first premise is not provable, as it requires a partial decoder which can disambiguate between formatted values with arbitrary tails, and no such function exists. Defining our decoder derivation rules using CorrectDecoder forces them to produce partial decoders that are compatible with \( +_D \).

We also note that all three rules are parameterized over a predicate \( P \) that is used to restrict the source format \( P \cap \text{format} \). This predicate is used to retain information about previously decoded data, which is necessary for many standardized binary formats, where there is some dependency between the values encoded by different subformats. Outside of encoding the number of elements in a variable-length list (often not directly adjacent to the list itself), as in Section 1.1, examples include tags for sum types, version numbers, and checksum fields. In each case, how a particular subformat is decoded is influenced by a previously decoded value on which it depends. The correctness of these decoders similarly depends on previously decoded values: correct use of the list decoder depends on the accuracy of its length parameter, with respect to the original source value.

The decoder-derivation rule for sequences, DecSeq, uses \( P \) to thread this information through a derivation, while the DecTrm rule that ends a derivation exploits \( P \) to recover the original source value. To see how these rules fit
together, consider how this predicate evolves during the decoder derivation for the format presented at the top of Figure 5. Each intermediate node in this derivation corresponds to the format in the second premise of DecSeq. Note how each step introduces a variable for the newly parsed data, and how an additional constraint is added to P relating the original source value to this value. When the derivation reaches format_list, this constraint witnesses that the number of elements in that list is in hand. Similarly, although the format is empty at the topmost leaf of the derivation tree, P includes enough constraints to recover the original source value uniquely, and DecTm can be applied to finish the derivation. The first premise of DecTm ensures that the restriction on source values is sufficient to prove there exists some constant s’ which is equal to the original source value. The second premise of DecTm ensures that a derived decoder is not overly permissive in the case that P is too restrictive. While not the case here, a format could limit the value of a word-valued field, which would need to be validated during decoding. Thus, the function b in this premise acts as a decision procedure that validates any decoded data.

The final combinator in Figure 4, DecUnion, is similar to UnionEnc, with the key difference being that the function that selects which format to decode, n, does not have access to the original source value. Finding such an index function is obviously format-specific, and Narcissus’s automation currently relies on user-provided hints to do so.

![Figure 5. An example of constraints added to a format during a decoder derivation.](image)

### 2.4 Automating Derivations

Narcissus implements derive_encoder_decoder_pair via a pair of tactics, DeriveEncoder and DeriveDecoder. Both tactics are parameterized over libraries of derivation rules, rules, and can be extended to support new formats by adding new rules to their libraries.

\[
\mathcal{K} \in \text{Cont} \triangleq \text{DecodeM}_{ST} \rightarrow \text{DecodeM}_{ST}
\]

Conceptually, a decoder derivation rule is a partial function from a format to a (possibly empty) set of subformats and a continuation \( \mathcal{K} \) that builds a correct decoder from decoders for those subformats. These formats represent the premises of each combinator, while the continuation is the decoder in the conclusion of the rule. Thus, DecSeq from Figure 4 can be thought of as a function that returns the subformats \( P \cap \text{fmt} \) and \( \{s \mid f = s' \land P \} \cap \text{fmt} \) and the continuation \( \lambda d_1 d_2 d_3 . \epsilon \) when applied to a format of the form \( P \cap \text{fmt} \circ f = \text{fmt} \circ f \). A rule can fail to apply when its non-CorrectDecoder assumptions are not satisfied, e.g. DecUnion fails when an appropriate index function cannot be found. In the implementation of DeriveDecoder, each derivation rule is implemented as a tactic that attempts to discharge non-CorrectDecoder obligations via a combination of user-provided hints and rule-specific automation. The heart of DeriveDecoder is a recursive application of derivation rules, with the decoder constructed at each intermediate node being used to complete the derivation for the format that spawned it.

The pseudocode algorithm for DeriveDecoder is presented in Algorithm 1; DeriveEncoder has a similar algorithm. The algorithm first uses the Normalize function to standardize the input to the next step by applying the monad laws to normalize the format and simplifying the result. The next step uses the recursive ApplyRules function to implement a

#### Algorithm 1 Derive a decoder from a format

1. function DeriveDecoder(fmt, rules)
2. Input: fmt: a format relation
3. rules: set of decoder combinators
4. Output: dec: a decoder inverting fmt
5. ffmtb ← Normalize(fmt)
6. dec ← ApplyRules(ffmtb, rules)
7. return Optimize(dec)
8. function ApplyRules(fmt, rules)
9. match fmt with
10. case P ∩ ε ⇒ FinishDecoder(P)
11. case default ⇒
12. for rule ← rules do
13. try
14. (fmt, K) ← rule(fmt)
15. dec ← ApplyRules(fmt, rules)
16. return K(dec)
backtracking search for an implementation of the normalized format. ApplyRules first tests whether the current format has been completely processed, in which case it attempts to reconstitute the original source value using the FinishDecoder function, which we will discuss shortly. If the format is nonempty, the algorithm iteratively attempts to apply the available rules to the current format. If a rule is successfully applied, the algorithm recursively calls ApplyRules to derive decoders for any generated subformats. If those derivations are successful, the algorithm applies the continuation to the results and returns a finished decoder. If any subderivations fail, the algorithm moves on to the next available rule.

\[
H_1 : \text{length } s\text{.data} < 2^8 \land s\text{.stationId} = w
\]

\[
\lambda \text{length } s\text{.data} = l \land s\text{.data} = 1
\]

\[
\begin{array}{l}
\quad \text{Decompose ("destruct") the source value, s, with new variables for field values.}
\quad \hline
\quad \text{H}_1 : \text{length } s\text{.data} < 2^8 \land x_1 = w
\quad \lambda \text{length } x_2 = l \land x_2 = 1
\quad \hline
\quad \text{Substitute with equalities from source restriction (hypothesis } H_1\text{).}
\quad \hline
\quad \text{Variant of reflexivity solves the goal. } \square
\end{array}
\]

**Figure 6.** Example Ltac reconstruction of the original source value at the end of the derivation in Figure 5.

The algorithm distinguishes the FinishDecoder tactic that implements the TrmDec rule, as it deserves special discussion. FinishDecoder attempts to finish a derivation by finding instantiations of the s’ and b metavariables. Importantly, it cannot use the original source value for either, and must instead find values using only previously parsed data. Automatically finding an instance of s’ is particularly worrisome, as it is well-known that Ltac, Coq’s proof-automation language, does not provide good support for introspecting into definitions of inductive types, and we would like to use Ltac to construct records of fairly arbitrary types, without relying on OCaml plugins. Thankfully, a combination of standard tactics for case analysis and rewriting are up to the task.

To see how, consider the first proof obligation of TrmDec for the derivation from the previous section, which is presented in Figure 6. This figure denotes the unknown existential variable representing s’ as □s’. FinishDecoder first uses Coq’s standard destruct tactic to perform case analysis on s, generating the next subgoal presented in Figure 6, with occurrences of s replaced by its constructor applied to new variables x1, x2, and x3. FinishDecoder then attempts to remove any variables that are not in the scope of the existential variable by rewriting the current goal using any equalities in the context. The resulting final goal equates □s’ to previously decoded values and is solved by unifying the two sides via the reflexivity tactic. Importantly, since s was not available when □s’ was quantified, this final tactic only succeeds when the rewritten term depends solely on previously decoded data. FinishDecoder then attempts to solve a similar goal containing an existential variable for b by composing together known decision procedures and simplifying away any tautologies, relying on a special typeclass to resolve any user-defined predicates. As a final step, DeriveDecoder optimizes the final decoder function further by rewriting with the monad laws and byte-aligning the decoders.

Let format_IPv4_Packet (ip4 : IPv4_Packet) :=
format_IPChkSum
(format_const 0b0100 + format_nat 4 * IPv4_Packet_Header.Len
+ format_unused_word 8 + format_word + TotalLength
+ format_word + + format_unused_word 1
+ format_bool + DF + format_bool + MF
+ format_word + FragmentOffset + format_word + TTL
+ format_enum ProtocolTypeCodes + Protocol)
(format_word + SourceAddress + format_word + DestAddress
+ format_list format_word + Options).

**Figure 7.** Format for IP version 4 headers, using the IP Checksum format.

### 3 Extending the Framework

As outlined in Section 1.1, an extension to Narcissus consists of four pieces: a format, encoder and decoder functions, derivation rules, and automation for incorporating these rules into DeriveEncoder and DeriveDecoder. As a concrete example, consider the format of the Internet Protocol (IP) checksum used in the IP headers, TCP segments, and UDP datagrams featured in our case studies. Figure 8 presents the format, decoder, and decoder-derivation rule needed for Narcissus to support IP checksums. format_IPChkSum is a higher-order combinator in the spirit of + ; the key difference is that it uses the bytestrings produced by the two format parameters to build the IP checksum (the one’s complement of the bytestrings interpreted as lists of bytes), which it then inserts between the two encoded bytestrings in the output bytestring. decode_IPChkSum validates the checksum before decoding the rest of the string; the derivation rule for this format guarantees that this test will always succeed for uncorrupted data and that it can safely avoid parsing the rest of the input otherwise.

The decoder-derivation rule closely mirrors SeqDec, adding additional assumptions that the bytestrings produced by each subformat have constant length and are properly byte-aligned; these assumptions are needed to prove the validity of the initial checksum test. The tactic that integrates the
rule into DeriveDecoder attempts to discharge the first four assumptions by using a database of facts about the lengths of encoded datatypes and the modulus operator, relying on DeriveDecoder to derive decoders for the subformats. Figure 7 presents an example of the checksum combinator being used in the format for the IP headers. Derivation of the decoder then follows automatically, once the hint database is stocked with suitable lemmas. (The specific example from the figure needs no hints not already registered by our Narcissus base library, with one length rule per primitive combinator.)

4 Evaluation

To evaluate the expressiveness and real-world applicability of Narcissus, we wrote specifications and derived implementations of encoders and decoders for six of the most commonly used packet formats of the Internet protocol suite: Ethernet, ARP, IPv4, TCP, UDP, and DNS. These formats were chosen to cover the full TCP/IP stack while offering a wide variety of interesting features and challenges:

Checksums. An IPv4 packet header contains a checksum equal to the one’s-complement sum of the 16-bit words resulting from encoding all other fields of the header.

Pseudoheaders. TCP and UDP segments also contain checksums, but they are computed on a segment’s payload prefixed by a pseudoheader that incorporates information from the IP layer. This pseudoheader is not present in the encoded packet.

Unions. An Ethernet frame header contains a 16-bit EtherType field, encoding either the length of the frame’s payload (up to 1500 bytes) or a constant indicating which protocol the frame’s payload encapsulates. The two interpretations were originally conflicting, but the ambiguity was resolved in IEEE 802.3x-1997 by requiring all EtherType constants to be above 1535. This dichotomy is easily expressed in Narcissus as a union format.

Compression. DNS messages can optionally be compressed, using a scheme in which repeated strings may be replaced by pointers to previous occurrences in the packet.

Variant types. DNS messages can encode various resource records, each of which includes data specific to its record type, prefixed with a type identifier and a length field.

Constraints and underspecification. TCP, UDP, and IP headers include underspecified or reserved-for-future-use bits, as well as fields with interdependencies (for example, the 16-bit urgent-pointer field of a TCP packet is only meaningful if its URG flag is set, and the options of a TCP packet must be zero-padded to a 32-bit boundary equal to that specified by the packet’s data-offset field).

The specifications of these formats are short and readable: new formats typically requires 10 to 20 lines of declarative serialization code and 10 to 20 lines of record-type, enumerated-type, and numeric-constant declarations (the DNS specifications are about six times larger, due to the additional complexity). In addition to the base set of formats, these specifications leverage a few TCP/IP-specific extensions including checksums, pseudoheader checksums, DNS compression, and custom index functions for union types.

The decoders that our framework produces are reasonably efficient and sufficiently full-featured to be used as drop-in replacements for all encoding and decoding components of a typical TCP/IP stack. In the rest of this section, we describe our extraction methodology and support our claims by presenting performance benchmarks and reporting on a fork of the native-OCaml mirage-tcpip library used in the MirageOS unikernel, rewired to use our code to parse and decode network packets. We use Coq’s extraction mechanism to obtain a standalone OCaml library, using OCaml’s integers to represent machine words and natural numbers, a native-code checksum implementation, and custom array data structures for the bytestrings and vectors that encoders and decoders operate on. These custom data structures, as well as a subset of the rewrite rules used during the final byte-alignment phase, are unverified and thus part of our trusted base.

4.1 Benchmarking

Figure 9 shows single-packet encoding and decoding times, estimated by linearly regressing over the time needed to run batches of n packet serializations or deserializations for increasingly large values of n (complete experimental data, including 95% confidence intervals, are provided as supplementary material; they were obtained using the Core_bench OCaml library [22]).

4.2 Mirage OS Integration

MirageOS [29] is a “library operating system that constructs unikernels for secure, high-performance network applications”: a collection of OCaml libraries that can be assembled into a standalone kernel running on top of the Xen hypervisor. Security is a core feature of MirageOS, making it a natural
target to demonstrate integration of our encoders and decoders. Concretely, this entails patching the mirage-tcpip\textsuperscript{2} library to replace its serializers and deserializers by our own and evaluating the resulting code in a realistic network application. We chose the mirage.io website (mirage-www on OPAM), which shows that the overhead of using our decoders in a real-life application is very small.

**Setup** After extracting the individual encoders and decoders to OCaml, we reprogrammed the TCP, UDP, IPv4, ARPv4, and Ethernet modules of the mirage-tcpip library to use our code optionally, and we recompiled everything. This whole process went smoothly: Mirage’s test suite did not reveal issues with our proofs, though we did have to adjust or disable some of Mirage’s tests (for example, one test expected packets with incorrect checksums to parse successfully, but our decoders reject them).

We strove to integrate into mirage-tcpip with minimal code changes: the vast majority of our changes affect the five files concerned with marshaling and unmarshaling our supported formats. This yields a good estimate of the amount of modification required (roughly 15 to 30 lines of glue code for each format), but it leaves lots of optimization opportunities unexplored: we incur significant costs doing extra work and lining up mismatched representations. Additionally, because we are strict about rejecting nonconforming packets, we perform new work that Mirage was not performing, such as computing checksums at parsing time or validating consistency constraints (Mirage’s packet decoders are a combination of hand-written bounds checks and direct reads at automatically computed offsets into the packets).

**Performance** To evaluate the performance of the resulting application, we ran the mirage-www server atop our modified mirage-tcpip and measured the time needed to load pages from the mirage.io website as we replaced each component by its verified counterpart (we repeated each measurement 250 times, using the window.performance.timing counters in Firefox to measure page load times). The incremental overhead of our verified decoders and encoders is minimal, ranging from less than 1% on small pages to 0.5-4% on large pages, such as the blog/ page of the MirageOS website (accessing it causes the client to fetch about 4.2 MB of data, obtained through 36 HTTP requests spread across 1040 TCP segments):

```
+ verified Ethernet encoding & decoding (+3.6%)
+ verified IPv4 encoding & decoding (+1.0%)
+ verified TCP encoding & decoding (+2.8%)
```

### 5 Related Work

**Parsers for Context-Free Languages** There is a long tradition of generating parsers for context-free languages from declarative Backus-Naur-form specifications [24, 36] automatically. Such generators may themselves have errors in them, so in order to reduce the trusted code base of formally verified compilers, there have been a number of efforts in verifying standalone parsers for a variety of context-free languages [10, 11, 25, 27, 39]. In closely related work, the authors of RockSalt [33] developed a regular-expressions DSL, equipped with a relational denotational semantics, in order to specify and generate verified parsers from bitstrings into various instruction sets. In subsequent work, Tan and Morisset [43] extended this DSL to support bidirectional grammars in order to provide a uniform language for specifying and generating both decoders and encoders, proving a similar notion of consistency to what we present here. Importantly, all of these works focus on languages that are insufficient for many network protocols. Additionally, these parsers produce ASTs for types defined by input grammars; these ASTs may need to be processed further (possibly using semantic actions) to recover original source values. This processing phase must itself be verified to guarantee correctness of the entire decoder.

**Verification of Parsers for Network Protocol Formats** A wide range of tools have been used to verify generated parsers for binary network protocol formats [6, 13, 37, 40, 42], including the SAW symbolic-analysis engine, [16], the Framac analyzer [14], F* [42], Agda [44], and Coq. The correctness properties of each project differ from Narcissus’s: Amin and Rompf [6] focus on memory safety. While Protzenko

\[\text{https://github.com/mirage/mirage-tcpip}\]

---

**Figure 9.** Processing times for various network packets on an Intel Core i7-4810MQ CPU @ 2.80GHz. Each row shows how each layer of the network stack contributes to encoding and decoding times. TCP and UDP checksums are computed over the entirety of the packet, payload included, which explains the higher processing times. The HTTP and ARP payloads are a GET request to http://nytimes.com and a clock-synchronization request to time.nist.gov.
et al. [37] and Collins et al. [13] prove that a pair of encoder and decoder functions satisfy a round-trip property similar to ours, relying on deterministic functions rules out many common formats, including DNS packets, Google Protocol Buffers, or formats using ASN.1’s BER encoding. In addition, some of these approaches only support constrained sets of formats: Collins et al. [13] are restricted to ASN.1 formats, while Simmons [40] requires the format to align with the source type. van Geest and Swierstra [44] also use a library of parsers and pretty printers for a fixed set of data types to build implementations, but they rely on verified datatype transformations to support a more flexible set of formats, including IPv4 headers.

**Parser-Combinator Libraries** There is a long history in the functional-programming community of using combinators [28] to eliminate the burden of writing parsers by hand, but less attention has been paid to the question of how to generate both encoders and decoders. Kennedy [26] presents a library of combinators that package serializers and deserializers for data types to/from bytestrings (these functions are also called picklers and unpicklers) into a common typeclass. A similar project extended Haskell’s Arrow class [23] with a reverse arrow in order to represent invertible functions [5]. In more closely related work, Rendel and Ostermann developed a combinator library for writing pairs of what they term partial isomorphisms [38]; that is, partial functions each of which correctly invert all values in the other’s range. The authors give a denotational semantics for their EDSL using a relational interpretation that closely mirrors Narcissus’s. Importantly, proofs of correctness for these libraries, where they exist, are strictly informal.

**Bidirectional / Invertible Programming Languages** Mu et al. present a functional language in which only injective functions can be defined, allowing users to invert every program automatically [34]. The authors give a relational semantics to this language, although every program in the language is a function. The authors show how to embed noninjective programs in their language automatically by augmenting them with sufficient information to invert each computation. They prove that this additional information can be dropped given a user-provided inversion function.

Boomerang [12] is a bidirectional programming language for projecting transformations on a data view back to the original source data; in contrast to Narcissus, Boomerang does not require that the original source values can be recovered from a target view. Boomerang programs are built using a collection of lens combinators, which include get, put, and create operations for transporting modifications between source and target representations. While Boomerang originally synthesized functions that assumed that every source value had a canonical target representation, it has since been extended with quotient lenses that relax this restriction [21]. The recently developed Optician tool [31] synthesizes Boomerang programs that implement bijective string transformations from regular expressions describing source and target formats and sets of user-provided disambiguating examples. The format-decoding problem differs from the lens setting in that lenses consider how to recover a new source value from an updated target value given full knowledge of the old source value, while decoding must work given only a single target value.

**Extensible Format-Description Languages** Interface generators like XDR [41], ASN.1 [17], Apache Avro [7], and Protocol Buffers [45] generate encoders and decoders from user-defined data schemes. The underlying data format for these frameworks can be context-sensitive, but this format is defined by the system, however, preventing data exchange between programs using different frameworks. The lack of fine-grained control over the target representation prevents users from extending the format, which could bring benefits in dimensions like compactness, even ignoring the need for compatibility with widely used standards.

The binpac compiler [35] supports a data-format-specification language specifically developed for network protocols but does not support extending the language beyond the built-in constructs. More recent frameworks, like PADS [18], PacketTypes [30], and Datastream [8], feature sophisticated data-description languages with support for complex data dependencies and constraints for specific data schemes but also lack support for extensions. Nail [9] is a tool for synthesizing parsers and generators from formats in a high-level declarative language. Nail unifies the data-description format and internal data layout into a single specification and allows users to specify and automatically check dependencies between encoded fields. More importantly, Nail natively supports extensions to its parsers and generators via user-defined stream transformations on the encoded data, allowing it to capture protocol features that other frameworks cannot. However, Nail provides no formal guarantees, and these transformations can introduce bugs violating the framework’s safety properties. We also note two other differences between Nail and Narcissus. First, Nail has many more orthogonal primitives than Narcissus, as our primitives may be considered to be little more than the definition of decoder correctness. Second, while Nail provides flexibility in describing binary formats, it maps each format to a fixed C struct type, where Narcissus is compatible with arbitrary Coq types.

**6 Conclusion**

In conclusion, we have presented Narcissus, a framework for specifying and deriving correct-by-construction encoders and decoders for non-context-free formats in the style of parser-combinator libraries. This framework provides fine-grained control over the shape of encoded data, is extensible with user-defined formats and implementation strategies, has a small set of core definitions augmented with a library of
common formats, and produces machine-checked proofs of soundness for derived decoders and encoders. We evaluated the expressiveness of NARCISUS by deriving decoders and encoders for several standardized formats and demonstrated the utility of the derived functions by incorporating them into the OCaml-based Mirage operating system.

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