# Datatype Generic Packet Descriptions

#### joint work with Marcell van Geest

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#### About me

- Studied Mathematics and Computer Science in Utrecht
- PhD from University of Nottingham
- Postdocs at Chalmers and Nijmegen
- OCaml developer at Vector Fabrics
- Now Assistant Professor at Utrecht University

I've worked with all kinds of functional languages and interactive proof assistants.

I'm now visiting Galois on sabbatical for the summer.



#### The problem

Data comes in all kinds of shapes and sizes.

Some of the formats and protocols used to store or transmit information in binary can be quite complex.



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#### Example: IPv4 header

Offsets	Octet					0					1								2									3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	1	L	12	13	14	15	16	1	7 1	3 1	19	20	21	22	23	24	1 2	5 26	5	27 2	8 2	9	30 3
0	0		Version IHL										DSCP ECN						Total Length																
4	32		Identification Flags Fragment Offset																																
8	64	Time To Live									Protocol							Header Checksum																	
12	96	Source IP Address																																	
16	128	Destination IP Address																																	
20	160																																		
24	192																																		
28	224	Options (if IHL > 5)																																	
32	256																																		



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#### Example: IPv4 packets

- ▶ The Version field must be equal to 0100 (i.e. 4)
- The Internet Header Length (IHL) specifies the number of 32-bit words the header is long. It must be at least 5;
- The Header Checksum occurs halfway through the header.
- The Total Length specifies the length of the packet in bytes. From the IHL and Total Length fields you can compute the length of the remaining data.



#### Problems

#### Parsing IPv4 is not easy.

The grammar is beyond context free: computing the length of the data or checksum involves non-trivial computations.



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This is usually done through some combination of natural language, pseudocode, C structs/unions, RFCs,...

Can we do better?



# This talk

We will try to design a **data type** for describing various binary formats.

From such descriptions, we can *generate* parsers and pretty printers.



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By embedding this construction in a dependently typed programming language – such as Coq, Agda, or Idris – we can prove the desired round trip property relating parsing and pretty printing.



# This talk

We will try to design a **data type** for describing various binary formats.

From such descriptions, we can *generate* parsers and pretty printers.

By embedding this construction in a dependently typed programming language – such as Coq, Agda, or Idris – we can prove the desired round trip property relating parsing and pretty printing.

Crucially, we will use *dependent types* to mix computation and static type safety.



#### Warm up: universes

data FT : Set where word : (n :  $\mathbb{N}$ )  $\rightarrow$  FT  $\_\otimes\_$  : FT  $\rightarrow$  FT  $\rightarrow$  FT

A pair of a data type that describes a collection of types (FT) and the decoding function mapping descriptoins to their corresponding types is sometimes known as a **universe**.



# Generating parsers from descriptions

```
Parser : Set \rightarrow Set
Parser a = List Bit \rightarrow Maybe (a × List Bit)
```

parse : (f : FT)  $\rightarrow$  Parser [ f ]] parse (t<sub>1</sub>  $\otimes$  t<sub>2</sub>) = \_,\_ <\$> parse t<sub>1</sub> <\*> parse t<sub>2</sub> parse (word n) = take n where take : (n :  $\mathbb{N}$ )  $\rightarrow$  Parser (Vec n Bit)



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#### Pretty printing data

#### 



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#### Round trip correctness

roundTrip : (f : FT) 
$$\rightarrow$$
 (x : [[f]])  $\rightarrow$   
parse f (pp f x) == just (x, [])

Proof by induction on our description f.



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# Limitations

- This gives us a very limited language for describing products of fixed size words.
- There are no dependencies between a field and the type of the remaining fields, e.g., a length field specifying the size of the remaining data;
- There are no constraints on the values that fields may assume, e.g., a checksum field that is computed from all other fields or a constant field that must be equal to 0100.



#### Interlude: sigma types

data Pair (a : Set) (b : Set) : Set where \_,\_ : a  $\rightarrow$  b  $\rightarrow$  Pair a b

Note: the type of the constructor is *not* dependent.

What if the type of the second component can depend on the value of the first?



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Note: the type of the constructor is *not* dependent.

What if the type of the second component can depend on the value of the first?

data  $\Sigma$  (a : Set) (b : a  $\rightarrow$  Set) : Set where \_,\_ : (x : a)  $\rightarrow$  b x  $\rightarrow$   $\Sigma$  a b

Constructive equivalent of existential quantification.



#### Take two

```
data FT : Set where
   word : (n : \mathbb{N}) \rightarrow FT
   \_\otimes\_ : FT \rightarrow FT \rightarrow FT
   calc : (t : FT) \rightarrow [ t ] \rightarrow FT
   sigma : (t : FT) \rightarrow (\llbracket t \rrbracket \rightarrow FT) \rightarrow FT
\llbracket \_ \rrbracket : FT \rightarrow Set
[ word n ] = Vec Bit n
 \mathbf{t}_1 \otimes \mathbf{t}_2 ] = [ \mathbf{t}_1 ] \times [ \mathbf{t}_2 ]
[calc t v ]] = ⊤
 sigma t f ] = \Sigma [ t ] (\ v \rightarrow [ f v ])
```

This universe now relies on induction recursion.



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# Examples: checksum

```
checksumedByte : FT
checksumedByte =
sigma (word 7) (\ d \rightarrow calc (word 1) (parity d))
where
parity : Vec Bit n \rightarrow Bit
```

- A 7 bit word;
- Followed by a single parity bit.



# Examples: checksum

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```

- A 7 bit word;
- Followed by a single parity bit.

The corresponding type [ checksumedByte ]] is

 $\Sigma$  (Vec Bit 7) (\d  $\rightarrow$   $\top$ )



# Examples: length field

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# lengthData : FT lengthData = sigma (word 32) (\ d $\rightarrow$ word (fromBits d)) where

fromBits :  $\llbracket Vec Bit n \rrbracket \rightarrow \mathbb{N}$ 

- A 32-bit word the length field;
- Followed by a word of that length;

#### **Examples: length field**

lengthData : FT lengthData = sigma (word 32) (\ d  $\rightarrow$  word (fromBits d)) where fromBits : [[ Vec Bit n ]]  $\rightarrow \mathbb{N}$ 

- A 32-bit word the length field;
- Followed by a word of that length;

The corresponding type [ lengthData ]] is:

 $\Sigma$  (Vec Bit 32) (\d  $\rightarrow$  Vec Bit (fromBits d))



Parsing sigma types is (almost) the same as parsing pairs; to parse derived fields, we parse the desired value and check it is what we expect.



We can update pretty printing and round trip proofs.



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In ideal world, where all binary formats are defined by type theorists, we would now be done.



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But...



We can update pretty printing and round trip proofs.

In ideal world, where all binary formats are defined by type theorists, we would now be done.

But...

- The computations involved are complicated! To make matters worse, we need to mix information about how to encode/decode data in the actual descriptions.
- Computed data (such as the header checksum in IPv4) may occur before all data on which it relies is present.



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# **Plan of attack**

- 1. Define a richer universe of file formats
- 2. Define a predicate that makes it clear when something is 'trivial' to parse/pretty print we can use this to generate the (de)serialization functions.
- 3. Define *transformations* on this richer universe, adding new fields or massaging data somehow.



#### Universe

data DT : Set<sub>1</sub> where leaf : Set  $\rightarrow$  DT  $\_\otimes\_$  : DT  $\rightarrow$  DT  $\rightarrow$  DT sigma : (c : DT)  $\rightarrow$  ([[c]]  $\rightarrow$  DT)  $\rightarrow$  DT [\_] : DT  $\rightarrow$  Set [leaf A]] = A [l  $\otimes$  r]] = [[1]]  $\times$  [[r]] [ sigma t f]] =  $\Sigma$  [[t]] (\ x  $\rightarrow$  [[f x]])

We define a universe closed under abritrary types, products, and dependent products.



#### Universe

#### data DT : Set<sub>1</sub> where leaf : Set $\rightarrow$ DT $\_\otimes\_$ : DT $\rightarrow$ DT $\rightarrow$ DT

- sigma  $\ :$  (c : DT)  $\rightarrow$  ([ c ]  $\rightarrow$  DT)  $\rightarrow$  DT
- This universe is 'large' it contains arbitrary other types. We can resolve this easily enough by parametrizing our development by a base universe.
- We arguably don't need both products and dependent products. We find it useful to distinguish between sequencing (products) and dependency (sigma types).



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#### Universe: example

```
length+word : DT
length+word = sigma (leaf \mathbb{N}) (\ len \rightarrow leaf (Vec Bits len))
```

This allows us to specify dependencies *independently* of the encoding – this is particularly useful as dependencies and computations become more complex.



Of course, these descriptions contain *arbitrary* data – in particular data such as functions that cannot be serialized easily.

If the description contains only binary words in the leaves, we can parse it easily enough.



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If the description contains only binary words in the leaves, we can parse it easily enough.

data IsL	<code>owLevel</code> : DT $ ightarrow$ Set where
leaf	: IsLowLevel (leaf (Vec Bit n))
pair	: IsLowLevel 1 $ ightarrow$
	IsLowLevel r $ ightarrow$
	IsLowLevel (l $\otimes$ r)
sigma	: IsLowLevel c $\rightarrow$
	((x : $\llbracket$ c $\rrbracket$ ) $ ightarrow$ IsLowLevel (d x)) $ ightarrow$
	IsLowLevel (sigma c d)



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. . .

#### data IsLowLevel : DT $\rightarrow$ Set where

parse : (f : FT)  $\rightarrow$  IsLowLevel f  $\rightarrow$  Parser [[ f ]]

The definition of parse is pretty much identical to what we saw previously.

Proofs of the IsLowLevel predicate can be generated automatically for most formats.



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#### data <code>IsLowLevel</code> : <code>DT</code> $\rightarrow$ <code>Set</code> where

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Proofs of the IsLowLevel predicate can be generated automatically for most formats.

Assuming all data is binary words, we can call our parse function. But what if it isn't?



#### Conversions

We can specify how to convert from one representation to another:

 $\begin{array}{l} \text{data Conversion } (t_1 \ t_2 \ : \ \text{DT}) \ : \ \text{Set where} \\ \text{convert} \ : \ (\text{enc} \ : \ \llbracket \ t_1 \ \rrbracket \rightarrow \ \llbracket \ t_2 \ \rrbracket) \rightarrow \\ & (\text{dec} \ : \ \llbracket \ t_2 \ \rrbracket \rightarrow \ \text{Maybe} \ \llbracket \ t_1 \ \rrbracket) \rightarrow \\ & ((x \ : \ \llbracket \ t_1 \ \rrbracket) \rightarrow \ (\text{dec (enc } x) \ \equiv \ \text{just } x)) \\ & \text{Conversion } t_1 \ t_2 \end{array}$ 

This is a *semi-partial isomorphism* – or shift in representation – between two types,  $[t_1]$  and  $[t_2]$ .



## **Categories of conversions**

These conversions are closed under composition.

And we can define an identity conversion:

idConvert : Conversion t t



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# Example: Explicit Congestion Notification (ECN)

data ECN : Set where Non-ECT : ECN ECT0 : ECN ECT1 : ECN CE : ECN

```
enc : ECN \rightarrow Vec Bit 2
dec : Vec Bit 2 \rightarrow ECN
enc-dec : (x : ECN) \rightarrow dec (enc x) \equiv just x
```

Conversions describe the shift in representation of *one* field – but how do we extend this to handle a complete description?



## **Converting descriptions**

#### 

You can think of DTX t as a transformation on the description t – applying certain data conversions at specific points in the description.

Once again, there is an identity transformation and we can compute the reflexitive-transitive closure, DTX\*.



## Example: converting natural numbers to bits

```
length+word : DT
length+word = sigma (leaf \mathbb{N}) (\ len \rightarrow leaf (Vec Bits len))
```

```
length+word+enc : DTX length+word
length+word+enc = sigma int32 (\ len \rightarrow copy)
where
    int32 : Conversion \mathbb{N} (Vec Bit 32)
    copy : Conversion t t
```



## Example: converting natural numbers to bits

```
length+word : DT
length+word = sigma (leaf \mathbb{N}) (\ len \rightarrow leaf (Vec Bits len))
```

```
length+word+enc : DTX length+word
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where
    int32 : Conversion \mathbb{N} (Vec Bit 32)
    copy : Conversion t t
```

Describing the lengths of IPv4 packets in this style is really worth the additional effort.



# Calculating new types and values

extendType :  $DTX t \rightarrow DT$ 

extendValue : (tx : DTX t)  $\rightarrow$  $\llbracket \texttt{t} \rrbracket \rightarrow \llbracket \texttt{extendType tx} \rrbracket$ 

Using these functions we can calculate a new modified description, call the corresponding parser, and convert the result back to the desired format



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There were two problems we set out to solve initially:

The computations need to mix information about how to encode/decode data in the actual descriptions.



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The computations need to mix information about how to encode/decode data in the actual descriptions.

#### Done

 Computed data (such as the header checksum in IPv4) may occur before all data on which it relies is present.

How can we *add new fields* to existing descriptions?



### Idea: a new constructor for the DTX type

```
data DTX (top : DT) : DT \rightarrow Set where ... insert : ...
```

We add a new type parameter to the DTX type, representing the 'global' description that we're transforming.

We add a new constructor to the DTX type, inserting new fields to an existing description.



#### Idea: a new constructor for the DTX type

```
data DTX (top : DT) : DT \rightarrow Set where
```

```
\begin{array}{rrrr} \text{insert} : (\texttt{t'} &: \texttt{DT}) \to \texttt{Side} \to (\llbracket \texttt{top} \ \rrbracket \to \llbracket \texttt{t'} \ \rrbracket) \\ & \to \texttt{DTX} \texttt{top t} \end{array}
```

```
data Side : Set where
  left right : Side
```

Calling insert t' left f – inserts a field of type t' before the current format, calculated from the value of all the other fields ([[ top ]]) using the function f.



# Example: inserting a checksum

t : DT
t = length+word+enc
checksummed : DTX t t
checksummed = insert (leaf Bit) left checksum
where
 checksum : [[t]] → Bit

Here we can insert a checksum bit *before* the remaining data.



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## Calculating new types and values

```
extendType : {t : DT} \rightarrow DTX top t \rightarrow DT
extendType {t = t} (insert t' left _) = t' \otimes t
extendType {t = t} (insert t' right _) = t \otimes t'
```

extendValue : (tx : DTX top t)  $\rightarrow$ [[ top ]]  $\rightarrow$  [[ t ]]  $\rightarrow$  [[ extendType tx ]] extendValue (insert t' left f) dtop d = (f dtop , d) extendValue (insert t' right f) dtop d = (d , f dtop)

Once again, given any description transformation (a value of type DTX), we can compute the resulting description and convert the results of parsing.



# Checking parsed values

Of course, we cannot decide whether or not a checksum is correct before parsing the remaining data. We can, however, read in the data and check it validity post hoc:

```
check : (tx : DTX t t) \rightarrow
[ extendType tx ] \rightarrow Maybe [ t ]
```

Alternatively, we can define single top-level function that parses and validates all data.



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#### **Drawbacks**

The type of the function used to compute derived fields in the insertion constructor is:

 $[\![ \ \mathsf{top} \ ]\!] \ \rightarrow \ [\![ \ \mathsf{t'} \ ]\!]$ 

Given the entire top-level data structure, we need to compute a value of type t'.

But what if we want to perform *conditional* extensions on existing data?



## Example: maximum element of a vector

```
vecBits : DT
vecBits = sigma \mathbb{N} (\ len \rightarrow Vec Bit len)
insertMax : DTX vecBits vecBits
insertMax = sigma copy iMax
where
iMax : (len : \mathbb{N}) \rightarrow DTX vecBits (Vec \mathbb{N} len)
iMax zero = copy
iMax (suc n) = insert \mathbb{N} right maxVec
maxVec : [ vecBits ] \rightarrow \mathbb{N}
```

We need to compute the maximum of *any* vector, even if we only want to add a new field to *non-empty* vectors.



# Solution

The argument to insert that calculates new values has the type:

```
[\![ \ \mathsf{top} \ ]\!] \\ \rightarrow [\![ \ \mathsf{t'} \ ]\!]
```

We want to make it more specific, allowing it to refer to the current subtree:

In our maximum vector example, this would correspond to having a non-empty vector as argument, rather than having to handle all possible cases.



## Selection (sketched)

To make the type of insertion more precise, we update the type of our transformations:

```
data \_\triangleright\_ : DT \rightarrow DT \rightarrow Set where
```

```
•••
```

```
data DTX (top : DT) :

(t : DT) \rightarrow (s : top \triangleright t) \rightarrow Set where

_\otimes_ : DTX top l (s >> fst) \rightarrow

DTX top r (s >> snd) \rightarrow

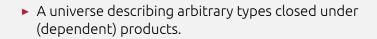
DTX top (l \otimes r) s
```

This lets us give the more precise type to the insert constructor.



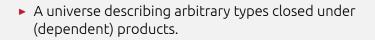
A universe describing arbitrary types closed under

(dependent) products.



 A predicate stating when elements of this universe are 'easy' to parse.

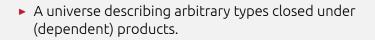




- A predicate stating when elements of this universe are 'easy' to parse.
- Generic parse and pretty print functions satisfying the expected round trip property.



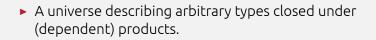
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- A predicate stating when elements of this universe are 'easy' to parse.
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- Transformations allowing you to modify data representation or insert new fields.



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- A predicate stating when elements of this universe are 'easy' to parse.
- Generic parse and pretty print functions satisfying the expected round trip property.
- Transformations allowing you to modify data representation or insert new fields.

Together this gives you a 'DSL' for describing binary data.



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#### Case study: IPv4

Offsets	Octet		0									1								2									3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	1	L	12	13	14	15	16	1	7 1	3 1	19	20	21	22	23	24	1 2	5 26	5	27 2	8 2	9	30 3	
0	0		Version IHL									DSCP ECN							Total I									Len	Length							
4	32		Identification Flags Fragment Offset																																	
8	64		Time To Live Protocol Header Checksum																																	
12	96		Source IP Address																																	
16	128			Destination IP Address																																
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24	192																																			
28	224																Optio	ons (	IT IHI	L >	> 5)															
32	256																																			



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#### **Types of fields**

- Enumerations such as the ECN or Protocol fields these are easy to model in Agda; we can describe their low-level encodings later using a suitable conversion.
- (Bounded) natural numbers the Total Length or Internet Header Length are big-endian integers. We typically use Fin (2 ^ 32) to describe a 32-bit integer – this makes the computations using these fields easier. Conversions describe how to serialize such values to words.



# Types of fields (continued)

- Constants the Version field must be 0100. These can be inserted into a description.
- Variable length words the Data and Options field contain words of variable length. Using sigma types we can capture the dependency between fields. The calculations involved can be a bit messy...



## Results

Complete description of IPv4 in four steps:

- 1. Basic definition describing the data stored in a packet.
- 2. Insert constant fields and converting convenient lengths to their actual representation.
- 3. Binary encoding of all high-level data.
- 4. Insertion of checksums.

Compiled to Haskell and tested against existing IPv4 implementations.



## Results

Complete description of IPv4 in four steps:

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- 3. Binary encoding of all high-level data.
- 4. Insertion of checksums.

Compiled to Haskell and tested against existing IPv4 implementations.

Found a bug in our implementation – choice of big-endian vs. little-endian of integers.



#### **Further work**

- Better error messages when parsing fails.
- Named fields either using Strings, reflection, or singleton types.
- Proofs of (in)equalities are no fun in Agda.



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In this domain, we've studied how to *transform* such descriptions to accommodate for external constraints, imposed by existing binary formats.



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Instead of writing arbitrary transformations on descriptions, we have a 'deep embedding' of various well-behaved transformations.



Data type generic programming uses type structure to derive new functions.

In this domain, we've studied how to *transform* such descriptions to accommodate for external constraints, imposed by existing binary formats.

Instead of writing arbitrary transformations on descriptions, we have a 'deep embedding' of various well-behaved transformations.

From these transformations, we can calculate new type descriptions and their associated parsers for realistic binary formats.



#### Questions?



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