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A formal semantics for ASN.1

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What is ASN.1?

- A data description language
- Describes the structure of data to be transmitted over wires (cf. XML schemas)
- Conventional collection of primitive data types: booleans, integers, strings, time types; plus enumerations, records, sum types
- Choice of several encoding schemes
- Specifications can span several modules
- Modules can be mutually-referential

ASN.1 is everywhere

- Many IETF RFCs
- X.509, SNMP, X.400, X.500
- SSL/TLS
- Code for ASN.1 types in every OS, browser

Example ASN.1 module

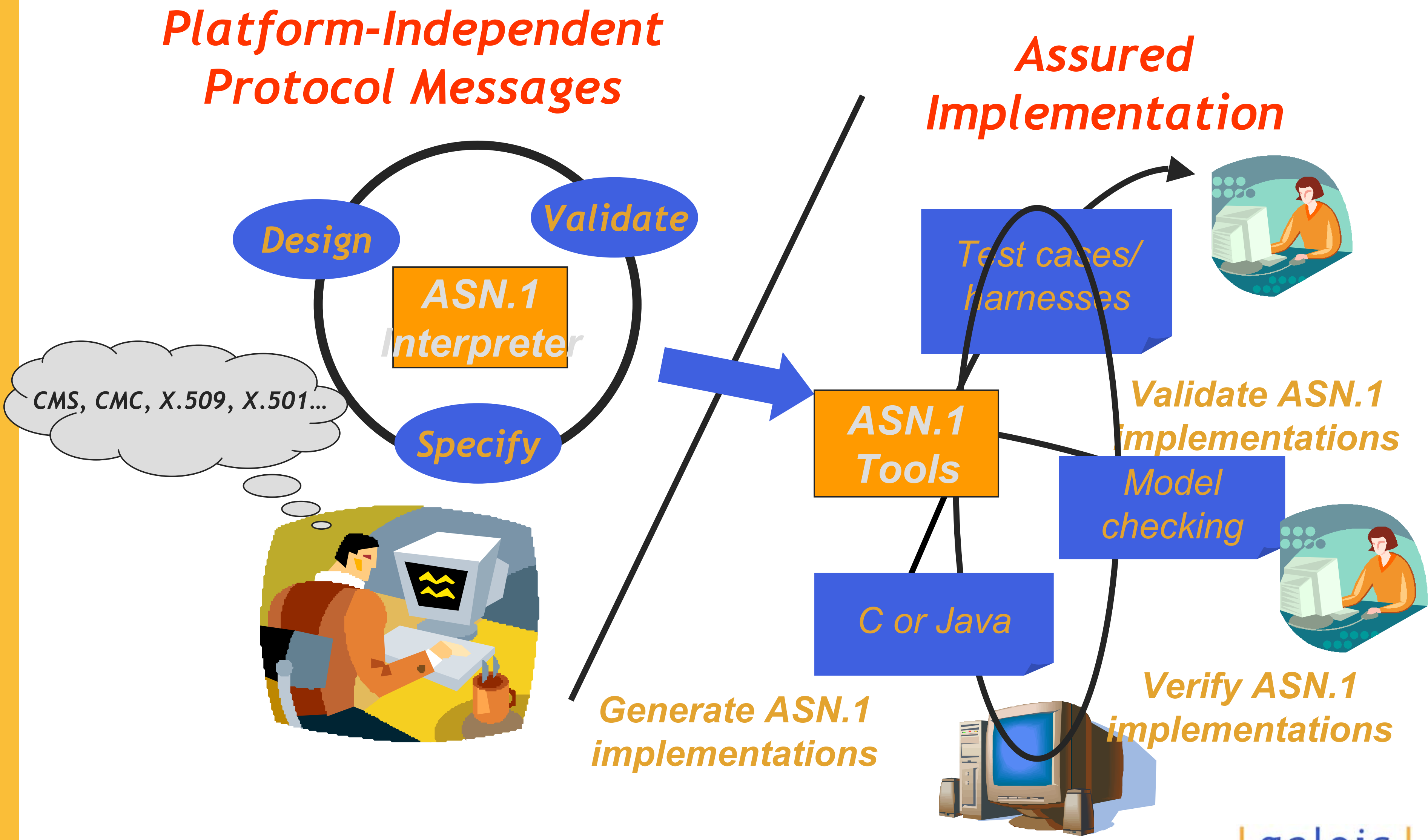
```
MyModule
DEFINITIONS ::=
BEGIN
  EXPORTS ALL;
  IMPORTS;

  T0 ::= [1] INTEGER
  x T0 ::= 42

  T2 ::= [2] BIT STRING { a(1), b(x), c(3) }
  v2 T2 ::= c

END
```

Vision: High Assurance ASN.1 Workbench



Platform-Independent Protocol Messages

Design

Validate

ASN.1 Interpreter

Specify

CMS, CMC, X.509, X.501…

Assured Implementation

Test cases/ harnesses

ASN.1 Tools

Validate ASN.1 implementations

Model checking

C or Java

Generate ASN.1 implementations

Verify ASN.1 implementations

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Why a formal semantics?

- Except for the grammar defining the syntax, ASN.1 is specified entirely in English
- The ITU X.680 spec is mostly about syntax, not semantics
- Some of the subtleties are explained using examples in Annexes – not dispositive
- There's no reference implementation
- Potential for error if different compilers used for encoder and decoder

What to do with the semantics?

- Determine which ASN.1 specifications are legal
- If not legal, why not
- Give a meaning for a legal specification mean
- Exposes subtleties and ambiguities

Who wants a semantics?

- Tool implementers
- Users of ASN.1 tools
- ASN.1 specification writers
- ASN.1 standards writers
- Galois
  - Proof-of-concept compiler
  - Interpreter
  - Verifying compiler

What kind of semantics?

- Denotational semantics: mapping from source syntax to well-understood mathematical meaning
  - Meaning of a syntax phrase is compositional in the meaning of its subphrases
- In an ASN.1 specification, the interesting phrases are *type assignments*, *like*

```
T1 ::= INTEGER { x(42) }
```

- *And value assignments:*

```
v1 T1 ::= 5280
```

What are the denotations?

- *An ASN.1 compiler generates an encoder and decoder for each defined type*
- *So the semantics associates encoders and decoders with the types in type assignments*

Compositionality of denotations

- *Meaning of aggregate types, such as SEQUENCE, depends on the meaning of their components*
- *Meaning of a module is the union of the meanings for each type and value defined, producing type and value environments for the module*
- *Meaning of a set of modules is the union of the meaning of the modules, yielding global type and value environments*

Formal semantics: precedents

- R5RS, the last-published standard for Scheme, contained a denotational semantics for the lambda-calculus core
- The Standard ML programming language has had two versions of a formal semantics (1990, revised in 1997)
  - The ML Kit started as a direct implementation of the formal semantics
  - Compiler implementers can use the Kit as a check on their work, and a vehicle for experimentation

Scope of the semantics

The semantics covers a subset of ASN.1:

- X.680 only; no parameterization, no information objects, no general constraints
- No extensibility for enumerations, SEQUENCE, etc.
- No XML
- Supported types: BOOLEAN, INTEGER, ENUMERATED, BIT STRING, OCTET STRING, NULL, SEQUENCE/OF, SET/OF, CHOICE, OBJECT IDENTIFIER, RELATIVE-OID, most strings, time types
- Constraints: single value, range, size

The rest of the talk

- What does the semantics look like?
- How the semantics handles encoding rules
- Ambiguities and infelicities
- Type and value compatibility
- Status

Denotations in code

- ASN.1 syntax maps to Haskell expressions
  - An executable specification!
- We already have a representation of ASN.1 syntax from proof-of-concept compiler; some other recycled code
- Advantage of Haskell: the type system documents our logic and checks our work
- Meaning of a type assignment is an encoder / decoder pair, i.e., a pair of Haskell functions (plus some other administrative data)

Semantics for BOOLEAN

```
mk_en_de_bool :: MkEnDe
mk_en_de_bool = MkEnDe $ pairFuns mk_en_bool mk_de_bool
  where
    mk_en_bool tags = Encoder $
      \(ASN1Boolean b) ->
         DataStream [(tags,PrimDatum $ PrimBool b)]
    mk_de_bool tags = Decoder $
      (\ds -> case headDataStream ds of
               (tags',PrimDatum (PrimBool b))                    | tags == tags'
                   -> Just (ASN1Boolean b,tailDataStream ds)
               _    -> Nothing)
```

Semantics for SEQUENCE

```
seqTyMeaning asn1Envs tyNm ty mp synTags ctls =
  case ctls of
    SimpleComponents comTys         ->
      checkedMaybe (distinctElts $ map comTyNm comTys)
        (do
          compEnvs <- getComponentEnvs asn1Envs mp comTys
          Just $ mkSequenceCoders asn1Envs mp tyNm ty synTags
                   compEnvs)
  ...

getComponentEnvs :: ASN1_Envs -> ModuleParameters ->
  [ComponentType] -> Maybe [ComponentEnv]

mkSequenceCoders :: ASN1_Envs -> ModuleParameters ->
  IdentType -> Type -> [SyntacticTag] -> [ComponentEnv] ->
  TypeEnv
```

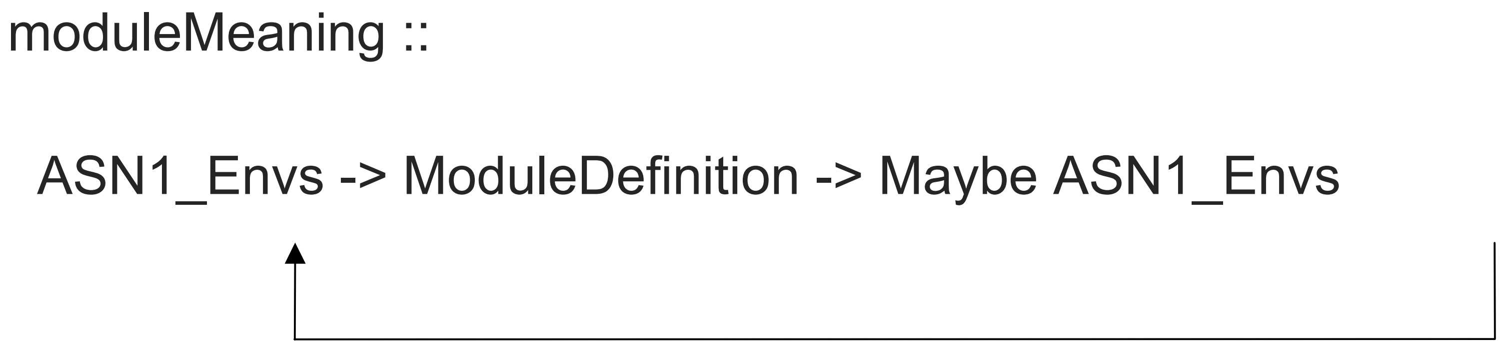
Semantics of a module

```
-- | meaning of a single module
moduleMeaning :: ASN1_Envs -> ModuleDefinition ->
  Maybe ASN1_Envs
moduleMeaning asn1Envs md =
  moduleBodyMeaning asn1Envs mb mp
  where
    mb = moduleBody md
    mp = moduleParmsFromModule md
```

Input environments are global; result is for this module only

Solving for environments

- The global environments input includes the per-module environments
  - For a single module, the input and output is the same environment pair



```
moduleMeaning ::

  ASN1_Envs -> ModuleDefinition -> Maybe ASN1_Envs
```

- Haskell's lazy evaluation allows such recursive definitions

Other data in type environments

The encoder/decoder pairs are parameterized over lists of tags

We associate lists of tags for each type:

T1 ::= [1][2][42] INTEGER
T2 ::= [18] T1

When encoding a T2 value, there are five tags to deal with

We also store any constraints associated with a type, to check values to be encoded, or the results of decoding

Alternative representations?

- Semantics should be a resource for ASN.1 users and implementers
- For broader dissemination, we could express the semantics as conventional mathematics
- A big job – about 5000 Haskell LOC
- For development, Haskell is type-checked, and it's executable

Abstracting over encodings

- There are several sets of rules for encoding types (BER, DER, PER, XER); plus roll-your-own encodings
- We split the semantics into encoding-independent and encoding-specific layers
- In the encoding-independent layer, we produce *abstract encodings*, which we call *data streams*
  - No octets

Example data stream

Given the type assignment

```
T1 ::= [101] BOOLEAN
```

here's the encoding of the value TRUE:

```
DataStream [ ([SemanticTag {semTagValue = ContextTag 101,
                            semTagApp = TaggedExplicit},
               SemanticTag {semTagValue = UniversalTag BooleanTag,
                            semTagApp = TaggedExplicit}],
              PrimDatum (PrimBool True))]
```

This is human-readable, unlike an octet list

A more complicated data stream

Given the type

`SEQUENCE { foo INTEGER, bar BOOLEAN }`

the encoding of { foo 42, bar TRUE } yields:

```
DataStream
 [([SemanticTag {semTagValue = UniversalTag SequenceTag,
semTagApp = TaggedExplicit}],
   AggregateToken SequenceToken),
  ([SemanticTag {semTagValue = UniversalTag IntegerTag,
semTagApp = TaggedExplicit}],
    PrimDatum (PrimInteger 42)),
  ([SemanticTag {semTagValue = UniversalTag BooleanTag,
semTagApp = TaggedExplicit}],
    PrimDatum (PrimBool True))]
```

From abstract to concrete

- *Encodings are a vital part of the semantics of ASN.1*
- *An abstract data stream contains all the information we need to produce octets for any encoding (that's the goal, at least)*
- *Some information could be lost when going to the concrete level*
    - *For example, IMPLICIT tags overwrite other tags, so we couldn't recapture the original abstract data stream from octets alone*
- *We've implemented a translation between abstract data streams and DER*
    - *We build decoder when encoding, so no information is lost*

Type/value compatibility

- X.680 Annex B contains complicated notions of "identical type definitions" and "value mappings" between types
  - Not clear how to use these concepts, except from examples
  - Are examples exhaustive?
- Semantics uses a more principled notion of type and value compatibility

Type/value compatibility, cont.

```
 a T1 ::= v -- v is some value notation
b T2 ::= a
c T3 ::= b
```

we assess

- the value/type compatibility of v and T1
- the value/type compatibility of v and T2
- the value/type compatibility of v and T3
- the type/type compatibility of T1 and T2
- the type/type compatibility of T2 and T3

Type/value compatibility, cont.

```
 c ---> b ---> a ::= v
|      |      |
T3 :>  T2 :>  T1
```

where :> means

"there's at least one instance of the RH type that can be mapped to the LH type"

Even more principled ...

- We're working on a set of inference-rule style type rules
- Effectively the same as the code in the semantics, more elegantly presented
- To be shared between semantics and interpreter implementation

Lacunae

- Check that each type is instantiable, i.e., has at least one finite instance

- Consider:

  T1 ::= SEQUENCE { x BOOLEAN, y T1 }

  - Only infinite values in this case
  - Uninstantiability can be more subtle

- Algorithm by Rinderknecht could be added to semantics

- We're not checking that values appearing in a constraint contains at least one value denoted by the parent type:

  INTEGER (15..42) (11..14)

Status

- Coded, reviewed at Galois, outside semantics expert
- Tests:
  - Manual tests of each data type
  - Automatically generated tests, including multiple modules
  - Round-trip = encode/decode tests
- Review of semantics against X.680, clause-by-clause
  - Semantics is annotated with relevant sections of X.680
- Using semantics as a reference implementation for interpreter testing
  - Tried large number of QuickCheck-generated modules
  - Automated test harness

TODO

- Add support for more of ASN.1 to semantics
- Use implementation of type inference rules
- Check for type instantiability