

MASR — Meta Abstract Semantics Representation

Brian Beckman

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1 Abstract

Abstract Semantics Representation (ASR) is an innovative intermediate representation¹ (IR) for multiple LCompilers.² ASR is independent of the particular programming language under compilation. Current compiler front-ends targeting ASR include LFortran³ and LPython.⁴ ASR is also agnostic to the compiler back end. Current back ends targeted *from* ASR include LLVM, x86, C, and WASM⁵

Being agnostic means that it is easy to write new compilers, both at the front end and the back end. For example, LFortran predates LPython. When the need for a Python compiler arose, only a Python front end was necessary. Within a few days, a new end-to-end compiler, LPython, was created.

LCompiler back ends are completely reusable because ASR eliminates all original language syntax from the IR, in sharp contrast to typical practice, which treat semantics as decorations on syntax trees.

In addition to being more flexible, LCompilers are faster than average because optimizers are not hampered by useless syntactic structure.

Current specifications for ASR are written in ASDL,⁶ a metalanguage similar in spirit to yacc but less rich, by design.⁷ To build an LCompiler like LFortran or LPython, the ASDL grammar for ASR is parsed and a library, `asrlib`, in C++ is generated. Compiler front ends call this library to transform and emit ASR trees.

ASDL has several deficiencies, and MASR,⁸ described in this document, alleviates them. We aim to replace `asrlib` with MASR.

This document is pedagogical, both explaining MASR and teaching how to extend and maintain its Clojure code.

2 Issues with ASDL

2.1 ASDL is Moribund

ASDL has not progressed since originally published in 1987. We know of no other projects adopting ASDL. We should replace ASDL with a modern metalanguage that has a robust, lively ecosystem.

¹https://en.wikipedia.org/wiki/Intermediate_representation

²<https://github.com/lcompilers/libasr>

³<https://lfortran.org/>

⁴<https://lpython.org/>

⁵<https://webassembly.org/>

⁶https://en.wikipedia.org/wiki/Abstract-Type_and_Scheme-Definition_Language

⁷<https://en.wikipedia.org/wiki/Yacc>

⁸pronounced “maser;” it is a Physics pun

2.2 ASDL is Incomplete

All work with ASR is currently done with opaque binary representations and code written in C++. As usual with such, it's more time-consuming and error-prone than necessary to prototype, verify, validate, visualize, modify, and debug.

2.3 ASDL is Volatile

The ASDL for ASR changes frequently, for good reasons. However, stand-aside tools like `asr-tester`⁹ must chase the ASDL specification. Just keeping up with ASDL consumes almost all development time for `asr-tester`. We should unify the language for expressing ASR with the tools that verify and test ASR.

2.4 ASDL is Ambiguous

There are many syntactic and semantic ambiguities in the ASDL grammar. For example, the specification `integer*` might mean an ordered collection of `integer` or an unordered collection, with duplicate elements allowed or not.

ASDL cannot express such distinctions. In practice, the C++ implementations implicitly make these distinctions. In one place `integer*` means an ordered collection. In another place, `integer*` means an unordered collection, but only the generated C++ code knows where.

Hiding fine distinctions in specifications in the generated code is not good engineering practice in the face of a known better solution.

3 Clojure Solves ASDL Issues

ASR expressions, being trees, have a natural representation in S-Expressions.¹⁰ Clojure, being a modern Lisp, natively handles S-Expressions. Clojure is modern. Clojure has a robust, lively ecosystem.

Clojure.spec,¹¹ is a *force majeure* for precision, completeness, verification, and validation. The collection of MASR specs amounts to a meta-type system for ASR.

Clojure specs are arbitrary predicates, capable of expressing type-system logic beyond typical, hard-coded type systems. That flexibility affords new opportunities, say for experiments in dependent types and concurrency types.¹² In the short run, `clojure.spec` will make type constraints for ASDL explicit and manifest, and will relieve the burden on C++ programmers to manage implicit constraints.

This document may lag the Clojure code. It may also lag the current state of `asr-lib`, at least until MASR replaces `asr-lib`. The document mirrors an ASDL snapshot.¹³

⁹<https://github.com/rebcabin/asr-tester>

¹⁰<https://en.wikipedia.org/wiki/S-expression>

¹¹<https://clojuredocs.org/clojure.spec.alpha>

¹²<https://rholang.io/>

¹³https://github.com/rebcabin/masr/blob/main/ASR_2023_APR_06_snapshot.asdl

4 MASR Tenets

Hash-Maps — ASR entities shall be hash-maps with fully-qualified keywords as keys (see Section 6.1 for motivating example).

Multi-Specs — ASR entities shall be recursively checked and generated via Clojure multi-specs.¹⁴

Explicit — ASR entities shall contain all necessary information, even at the cost of verbosity. Defaults are not permitted.

Syntax Sugar — Constructor functions for ASR entities may allow default values for keyword arguments (see Section 6.11 for an example and see Issue 3 on MASR's GitHub repo).

¹⁴<https://clojure.org/guides/spec>

5 MASR Terms and Heads

Terms are the “objects” or “productions” of ASR, items to the left-hand side of an equals sign in the ASDL grammar. Table 1 exhibits terms that are

- explicitly specified in ASDL, like `symbol` or `dimension`
- used but not defined in ASDL, like `symbol_table`
- term-like but not defined in ASDL, like `identifier`

The definitions in Table 1 have been abbreviated and edited for presentation.

Heads are things like `Local` and `CaseStmt` that appear on the right-hand sides of terms equations in Table 1. There are of two kinds of heads:

function-like heads — have parentheses and typed parameters,
e.g., `CaseStmt (expr*, stmt*)`

enum-like heads — no parentheses, e.g., `Local`

MASR has a Clojure spec and syntactic sugar for each head. There are about 250 heads by a recent count.

Table 1: Terms (nodes) in the ASDL grammar (things left of equals signs):

term	partial expansion
1 unit	TranslationUnit(symbol_table, node*)
2 symbol	...many heads...
3 storage_type	Default Save Parameter Allocatable
4 access	Public Private
5 intent	Local In Out InOut ...
6 deftype	Implementation Interface
7 presence	Required Optional
8 abi	Source LFortranModule ... Intrinsic
9 stmt	...many heads...
10 expr	...many heads...
11 ttype	Integer(int, dimension*) ...
12 restriction_arg	RestrictionArg(ident , symbol)
13 binop	Add Sub ... BitRShift
14 logicalbinop	And Or Xor NEqv Eqv
15 cmpop	Eq NotEq Lt LtE Gt GtE
16 integerboz	Binary Hex Octal
17 arraybound	LBound UBound
18 arraystorage	RowMajor ColMajor
19 cast_kind	RealToInteger IntegerToReal ...
20 dimension	(expr? start, expr? length)
21 alloc_arg	(expr a, dimension* dims)
22 attribute	Attribute(ident name, attr-arg* args)
23 attribute_arg	(ident arg)
24 call_arg	(expr? value)
25 tbind	Bind(string lang, string name)
26 array_index	(expr? left, expr? right, expr? step)
27 do_loop_head	(expr? v, expr? start expr? end, expr? step)
28 case_stmt	CaseStmt(expr*, stmt*) ...
29 type_stmt	TypeStmtName(symbol, stmt*) ...
30 enumtype	IntegerConsecutiveFromZero ...
implicit	
31 symbol_table	Clojure maps
32 symtab_id	an int
*term-like	
0 dimensions	dimension*, via Clojure vectors or lists
0 atoms	int float bool nat bignat
0 identifier	by regex
0 identifiers	identifier*, via Clojure sets

6 Specs

The following sections

- summarize the Clojure specs for all ASR terms and heads
- pedagogically explain the architecture and approach taken in the Clojure code. The architecture is the remainder from several experiments. For example, `defrecord` and `defprotocol` for polymorphism was tried and discarded in favor of multi-specs.¹⁴

The tests in `core_test.clj` exhibit many examples that pass and, more importantly, fail the specs. The specs are written in the source file `specs.cl`. The best way to learn the code is to study the tests and to run them in the Clojure REPL or in the CIDER debugger in Emacs.¹⁵

We present the terms somewhat out of the order of Table 1. First is *intent*, as it is the archetype for several enum-like terms and heads.

6.1 intent

6.1.1 Sets for Contents

An ASR *intent* is one of the symbols

`Local`, `In`, `Out`, `InOut`, `ReturnVar`, `Unspecified`.

The spec for the contents of an intent is simply this set of enum-like heads. Any Clojure *set* (e.g., in `#{ ... }` brackets) doubles as a predicate function that tests for set membership. The result of the test is the candidate member if the candidate is present in the set. In the following two examples, the set appears in the function position of the usual Clojure function-call syntax (`function args*`):

```
(#{'Local 'In 'Out 'InOut 'ReturnVar 'Unspecified} 'Local)
```

`Local`

When the candidate element, say `fubar`, is not in the set, the result is `nil`, which does not print:

```
(#{'Local 'In 'Out 'InOut 'ReturnVar 'Unspecified} 'fubar)
```

Any predicate function can be registered as a Clojure spec.¹¹ Therefore the spec for *intent contents* is just the set of valid members. The name of the spec is `::intent-enum`.

6.1.2 Specs have Fully Qualified Keyword Names

The double colon in `::intent-enum` is shorthand; it implicitly signifies that `intent-enum` is a keyword in the namespace `masr.specs`. The names of all Clojure specs must be fully qualified in namespaces.

¹⁵<https://docs.cider.mx/cider/debugging/debugger.html>

The namespace `masr.specs` covers all names defined in the entire file `specs.clj`, where the syntax `::intent-enum` is valid. In files other than `specs.clj`, one explicitly writes the namespace, as in `:masr.specs/intent-enum`. More on that later.

```
(s/def ::intent-enum
  #{'Local 'In 'Out 'InOut 'ReturnVar 'Unspecified})
```

6.1.3 How to Use Specs

To check an expression like `'Local` against the `::intent-enum` spec, write

```
(s/valid? ::intent-enum 'Local)
;; => true
(s/valid? ::intent-enum 'fubar)
;; => false
```

To produce conforming or invalid entities inline to other code, write

```
(s/conform ::intent-enum 'Local)
;; => Local
(s/conform ::intent-enum 'fubar)
;; => :clojure.spec.alpha/invalid
```

To generate a few conforming samples, write

```
(gen/sample (s/gen ::intent-enum) 5)
;; => (Unspecified Unspecified Out Unspecified Local)
```

or, with conformance explanation (trivial in this case):

```
(s/exercise ::intent-enum 5)
;; => ([Out Out]
;;      [ReturnVar ReturnVar]
;;      [In In]
;;      [Local Local]
;;      [ReturnVar ReturnVar])
```

Strip out the conformance information as follows:

```
(map second (s/exercise ::intent-enum 5))
;; => (In ReturnVar Out In ReturnVar)
```

`s/valid?`, `s/conform`, `gen/sample`, and `s/exercise` pertain to any Clojure specs, no matter how complex or rich.

6.1.4 The Spec that Contains the Contents

`::intent-enum` is just the spec for the *contents* of an intent, not for the intent itself. The spec for the intent itself is an implementation of a polymorphic Clojure *multi-spec*¹⁴, `::asr-term`.

6.1.5 Multi-Specs

A multi-spec is like a tagged union in C. The multi-spec, `::asr-term`, as shown below, pertains to all Clojure hash-maps¹⁶ that have a tag named `::term` with a value like `::intent` or `::storage-type`, etc.

A multi-spec has three components:

defmulti¹⁷ — a polymorphic interface that declares the *tag-fetcher function*, `::term` in this case, which fetches a tag value from any candidate hash-map. The `defmulti` dispatches to a `defmethod` that matches the fetched tag value, `::intent` in this case. `::term` is a fully qualified keyword of course, but keywords double as tag-fetchers for hash-maps in Clojure.¹⁸

defmethod¹⁹ — individual specs, each implementing the interface; in this case, if the `::term` of a hash-map matches `::intent`, then the corresponding `defmethod` is invoked (see Section 6.1.7 below).

s/multi-spec — tying together the `defmulti` and, redundantly, the tag-fetcher.²⁰

6.1.6 Specs for All Terms

Start with a spec for `::term`:

```
;; like ::intent, ::symbol, ::expr, ...  
(s/def ::term qualified-keyword?)
```

The spec says that any fully qualified keyword, like `::intent`, is a MASR term. This spec leaves room for growth of MASR by adding more fully qualified keywords for more MASR types *qua* terms.

`s/def` stands for `clojure.spec.alpha/def`, the `def` macro in the `clojure.spec.alpha` namespace. The namespace is aliased to `s`.

Next, specify the `defmulti` polymorphic interface `term` (no colons) for all term specs:

```
(defmulti term ::term)
```

This `defmulti` dispatches to a `defmethod` based on the results of applying the keyword-*qua*-function `::term` to a hash-map:

```
(::term {::term ::intent ...})
```

equals `::intent`.

The spec is named `::term` and the tag-fetcher is named `::term`. They don't need to be the same. They could have different names.

¹⁶<https://clojuredocs.org/clojure.core/hash-map>

¹⁷<https://clojuredocs.org/clojure.core/defmulti>

¹⁸<https://stackoverflow.com/questions/6915531>

¹⁹<https://clojuredocs.org/clojure.core/defmethod>

²⁰Multi-specs allow re-tagging, but we do not need that level of generality.

6.1.7 Spec for intent

If applying `::term` to a Clojure hash-map produces `::intent`, the following spec, which specifies all intents, will be invoked. It must ignore its argument, `_`:

```
(defmethod term ::intent [_]
  (s/keys :req [::term ::intent-enum]))
```

This spec states that an *intent* is a Clojure hash-map with at least a `::term` keyword and an `::intent-enum` keyword. The `::intent-enum` sub-spec is recursively checked, as one can see in Section 6.1.9 below.

6.1.8 The Multi-Spec Itself: `::asr-term`

`s/multi-spec` ties `defmulti term` to the tag-fetcher `::term`. The multi-spec itself is named `::asr-term`:

```
;;      name of the mult-spec      defmulti  tag fn
;;      -----
(s/def ::asr-term (s/multi-spec term ::term))
```

6.1.9 Examples of Intent

The following shows a valid example:

```
(s/valid? ::asr-term
  {::term      ::intent,
   ::intent-enum 'Local})
```

true

Here is an invalid sample:

```
(s/valid? ::asr-term
  {::term      ::intent,
   ::intent-enum 'FooBar})
```

false

Generate a few valid samples:

```
(gen/sample (s/gen (s/and
  ::asr/asr-term
  #(= ::asr/intent (::asr/term %))))
  5)
;;=> (#::asr{:term ::asr/intent, :intent-enum ReturnVar}
  #::asr{:term ::asr/intent, :intent-enum In}
  #::asr{:term ::asr/intent, :intent-enum Unspecified}
  #::asr{:term ::asr/intent, :intent-enum Unspecified}
  #::asr{:term ::asr/intent, :intent-enum InOut})
```

6.1.10 Another asr-term: a Pattern Emerges

To define another asr-term, specify the contents and write a `defmethod`. The one multi-spec, `::asr-term`, suffices for all.

For example, another asr-term for an enum-like is `storage-type`:

```
(s/def ::storage-type-enum
  #{'Default, 'Save, 'Parameter, 'Allocatable})

(defmethod term ::storage-type [_]
  (s/keys :req [::term ::storage-type-enum]))
```

All enum-like specs follow this pattern.

6.1.11 Syntax Sugar

`{::term ::intent, ::intent-enum 'Local}`, a valid asr-term entity, is long and ugly. Write a short function, `intent`, via `s/conform`, explained in Section 6.1.3:

```
(defn intent [sym]
  (let [intent_ (s/conform
                    ::asr-term
                    {::term ::intent, ::intent-enum sym})]
    (if (s/invalid? intent_)
        ::invalid-intent
        intent_)))
```

Entities have shorter expressions:

```
(testing "better syntax"
  (is (s/valid? ::asr-term (intent 'Local)))
  (is (s/valid? ::asr-term (intent 'Unspecified)))
  (is (not (s/valid? ::asr-term (intent 'foobar))))
  (is (not (s/valid? ::asr-term (intent []))))
  (is (not (s/valid? ::asr-term (intent ())))))
  (is (not (s/valid? ::asr-term (intent {}))))
  (is (not (s/valid? ::asr-term (intent #{}))))
  (is (not (s/valid? ::asr-term (intent "foobar"))))
  (is (not (s/valid? ::asr-term (intent ""))))
  (is (not (s/valid? ::asr-term (intent 42))))
  (is (thrown? clojure.lang.ArityException (intent))))
```

All our specs are like that: a long-form hash-map and a short-form sugar function that does a conformance check.

6.2 unit

6.3 symbol

6.3.1 TODO Variable

6.4 storage_type

6.5 access

6.6 deftype

6.7 presence

6.8 abi

Abi is a rich case. It is enum-like, similar to *intent* (Section 6.1), but with restrictions. Its heads include several *external-abis*:

```
(def external-abis
  #{ 'LFortranModule, 'GFortranModule,
    'BindC, 'Interactive, 'Intrinsic})
```

and one *internal-abi*, specified as a Clojure set to get the membership-test functionality:

```
(def internal-abis #{'Source})
```

The *abi-enum* spec for the contents of an *abi* term is the unions of these two sets:

```
(s/def ::abi-enum
  (set/union external-abis internal-abis))
```

Specify an additional key in a conforming *abi* hash-map with a `::bool` predicate:

```
(s/def ::abi-external ::bool)
```

Add a convenience function for logic:

```
(defn iff [a b]
  (or (and a b)
      (not (or a b))))
```

Specify the `defmethod` for the *abi* itself with a hand-written generator (clojure.spec is not quite strong enough to create the generator automatically):

```
(defmethod term ::abi [_]
  (s/with-gen
    (s/and
      #(iff (= 'Source (::abi-enum %))
            (not (::abi-external %)))
      (s/keys :req [::term ::abi-enum ::abi-external]))
    (fn []
      (tgen/one-of
        [(tgen/hash-map
          ::term      (gen/return ::abi)
          ::abi-enum  (s/gen external-abis)
          ::abi-external (gen/return true))
         (tgen/hash-map
          ::term      (gen/return ::abi)
          ::abi-enum  (s/gen internal-abis)
          ::abi-external (gen/return false))] ))))
```

Generate a few conforming samples:

```
(gen/sample (s/gen (s/and
                  ::asr/asr-term
                  #(= ::asr/abi (::asr/term %))))
            5)
;; => (::asr{:term ::asr/abi,
;;       :abi-enum Interactive, :abi-external true}
;;     #::asr{:term ::asr/abi,
;;             :abi-enum Source, :abi-external false}
;;     #::asr{:term ::asr/abi,
;;             :abi-enum Source, :abi-external false}
;;     #::asr{:term ::asr/abi,
;;             :abi-enum Source, :abi-external false}
;;     #::asr{:term ::asr/abi,
;;             :abi-enum Source, :abi-external false}
;;     #::asr{:term ::asr/abi,
;;             :abi-enum Interactive, :abi-external true})
```

6.8.1 Syntax Sugar

The sugar for *abi* uses Clojure destructuring^{21, 22} for keyword arguments.

Conforming examples:

```
(abi 'Source      :external false)
(abi 'LFortranModule :external true)
(abi 'GFortranModule :external true)
(abi 'BindC       :external true)
(abi 'Interactive  :external true)
(abi 'Intrinsic   :external true)
```

Non-conforming due to incorrect boolean:

```
(abi 'Source      :external true)
(abi 'LFortranModule :external false)
(abi 'GFortranModule :external false)
(abi 'BindC       :external false)
(abi 'Interactive  :external false)
(abi 'Intrinsic   :external false)
```

²¹<https://clojure.org/guides/destructuring>

²²<https://gist.github.com/rebcabin/a3c24be3e17135f355348c834ab14141>

Non-conforming due to incorrect types or structure:

```
(abi 'Source :external 42)      ;; types are not ::bool
(abt 'Source :external "foo")  ;; /
(abt 'Source :external 'foo)   ;; ==
(abt 'Source false)           ;; no :external keyword
(abt 'Source true)            ;; /
(abt 'Source 42)               ;; /
(abt 'foo true)                ;; /
(abt 'foo false)              ;; ==
```

We don't show tests of incorrect arity.

Here is the implementation of the sugar, exhibiting the destructuring technique:

```
(defn abi
  "Destructure the keyword :external"
  [the-abi-enum, & {:keys [external]}]
  (let [abi_ (s/conform
    ::asr-term
    {::term ::abi,
     ::abi-enum the-abi-enum,
     ::abi-external external})]
    (if (s/invalid? abi_)
      ::invalid-abi
      abi_)))
```

6.9 stmt

6.10 expr

6.11 ttype

Ttype [sic] has a nested multi-spec. This is an archetype for all function-like heads, just as *intent* is an archetype for all enum-like heads.

```
(defmulti ttype-head ::ttype-head)
(defmethod ttype-head ::Integer [_]
  (s/keys :req [::ttype-head ::bytes-kind ::dimensions]))
(s/def ::asr-ttype-head
  (s/multi-spec ttype-head ::ttype-head))
```

```
(defmethod term ::ttype [_]
  (s/keys :req [::term ::asr-ttype-head]))
```

```
(s/valid? ::asr-term
  {::term ::ttype,
   ::asr-ttype-head
   {::ttype-head ::Integer,
    ::bytes-kind 4
    ::dimensions []}})
```

6.11.1 TODO Sugar

The sugar for ttypes is too permissive. On balance, we accept this fact. See Issue 3 on MASR's GitHub repo for discussion. This is subject to change. The following tests illustrate.

The fully-sugared specs for Integer, Real, Complex, and Logical take two keyword arguments, :kind and dimensions=:

```
(is (s/valid? ::asr/asr-ttype-head
  (Integer :kind 1, :dimensions [])))
(is (s/valid? ::asr/asr-ttype-head
  (Integer :kind 4, :dimensions [])))
(is (s/valid? ::asr/asr-ttype-head
  (Real :kind 8, :dimensions [])))
(is (s/valid? ::asr/asr-ttype-head (Real)))
```

Incorrect values for the keyword arguments are invalid:

```
(is (not (s/valid? ::asr/asr-ttype-head
  (Integer :kind 42))))
(is (not (s/valid? ::asr/asr-ttype-head
  (Integer :dimensions 'fubar))))
```

The keyword arguments default to `:kind 4` and `dimensions []`:

```
(is (= (s/conform ::asr/asr-tttype-head
              (Integer))
      (Integer :kind 4, :dimensions [])))
(is (= (s/conform ::asr/asr-tttype-head
              (Integer :kind 4))
      (Integer :kind 4, :dimensions [])))
(is (= (s/conform ::asr/asr-tttype-head
              (Integer :dimensions []))
      (Integer :kind 4, :dimensions [])))
```

The order of the keyword arguments does not matter:

```
(is (= (s/conform ::asr/asr-tttype-head
              (Integer :dimensions [], :kind 4))
      (Integer :kind 4, :dimensions [])))
```

Missing keywords are a **PITFALL**. The keyword values default to `nil`, which are replaced with the defaults `:kind 4` and `dimensions []`.

```
(testing "pitfalls -- sugar is too permissive"
  (is (= (s/conform ::asr/asr-tttype-head
                  (Integer 42 ['gobble-de-gook]))
        (Integer :kind 4, :dimensions []))))
```

- 6.12 `restriction_arg`
- 6.13 `binop`
- 6.14 `logicalbinop`
- 6.15 `cmpop`
- 6.16 `integerboz`
- 6.17 `arraybound`
- 6.18 `arraystorage`
- 6.19 `cast_kind`
- 6.20 `dimension`
- 6.21 `alloc_arg`
- 6.22 `attribute`
- 6.23 `attribute_arg`
- 6.24 `call_arg`
- 6.25 `tbind`
- 6.26 `array_index`
- 6.27 `do_loop_head`
- 6.28 `case_stmt`
- 6.29 `type_stmt`
- 6.30 `enumtype`
- 6.31 **Implicit Terms**

Terms used, explicitly or implicitly, but not defined in ASDL.

Some items specified in ASDL as *symbol_table* are actually *syntab_id*.

6.31.1 `syntab_id`

6.31.2 `symbol_table`

6.32 Term-Like Items

6.32.1 `dimensions`

6.32.2 `atoms`

6.32.3 `identifier`

6.32.4 `identifiers`

7 Change Log

2023-06-Apr :: Start.

2023-12-Apr :: enum-like specs