Abstract. Performance, genericity and flexibility are three valuable qualities for scientific environments that tend to be antagonistic. C++ provides excellent support for both performances and genericity thanks to its support for (class and function) templates. However, a C++ templated library can hardly be qualified as flexible: data of unexpected types cannot enter the system, which hinders user interactions. This paper describes the approach that was taken in the Vcsn platform to add flexibility on top of C++ templates, including runtime template instantiation.

1 Introduction

1.1 Performance, Genericity, Flexibility

In scientific environments dealing with large data (image or signal processing, graphs, computational linguistics...), performance, genericity and flexibility are three valuable qualities that tend to be antagonistic.

By performance, we mean the efficiency of both the data structures and the algorithms. By genericity, we mean the means to apply these structures and algorithms to a wide set of basic data types. By flexibility, we mean the ability to support new types at runtime, to support seamless interaction with the user, loading files, etc.

C++ excels at blending performance and genericity thanks to its excellent support of compile time code generation: templates. However, precisely because code generation is at compile time only, C++ is not flexible: one cannot write a C++ program that would load a standard list (std::list) for a type for which support was not compiled in. The world is closed at compile-time: new types cannot be introduced.

Actually, C++ provides some flexibility when traditional Object-Oriented Programming (OOP) is used, with virtual member functions, but it is known that in this case the performances are degraded. At the other end, so called dynamic languages such as Python offer excellent flexibility, and genericity: thanks to their dynamic typing, in interactive sessions, users can easily call algorithms on newly created data type, serialize data, etc. However, performances are poor.

This opposition shows in scientific libraries. For instance, consider the domain of graphs/networks. At one end lie heavily templated C++ libraries such as the Boost Graph Library (BGL) [28] which offers unparalleled genericity (at the
A1
0
b
b

a

1

A2
0
b

2a

b

2b

Fig. 1. Automaton $A_1$ is labeled by letters in \{a, b\}. Its states are 0 and 1. State 0 is initial, and State 1 is final. It features five transitions: \{((0, a, 0), (0, b, 0), (0, b, 1), (1, a, 1), (1, b, 1))\}. It accepts words on \{a, b\} with at least one b. The labels of Automaton $A_2$ are letters in \{a, b\}, its weights are in $\mathbb{Z}$. Implicit weights denote the neutral of the multiplication: b means 1b. Its context is $C_2 = \{a, b\} \rightarrow \mathbb{Z}$.

expense of being hard to tame) and excellent performances. However, because it relies on templates, it falls short on flexibility.

On the other hand of the spectrum, Networkx [14] also offers a wide range of algorithms, and great flexibility, because it is entirely written in Python. This comes at a cost: performance penalties such as 20x for single-source shortest path for instance, and sometimes much higher [20].

Somewhere in the middle, Graph-tool [21] offers the efficiency of C++ and the user friendliness of Python: its core is a Python binding of BGL. However this is at the expense of genericity: a finite set of parameters were chosen for BGL, and only this type of graphs is supported.

The domain of automata theory presents a similar pattern. A library such as OpenFst offers genericity (it supports a large range of automaton types) and a remarkable efficiency [3]. It is a templated C++ library. Conversely, the FAdo environment [4] is flexible, very user friendly, but offers poor performances. It is written in Python, with bits of C where Python is too slow.

This paper describes the approach that was taken in the Vesn platform to reconcile performance, genericity and flexibility in C++. We claim that this approach can be applied in various domains, under some conditions exposed further. However, because it was applied only once, and because we believe it is simpler exposed on a specific domain, this paper will focus on automata.

### 1.2 A Few Notions of Automata Theory

Finite automata are well studied (and commonly taught) devices that recognize languages, i.e., accept or refuse words. They are composed of a finite number of states, some of them being initial and/or final, and a set of transitions: triples (source, label, destination), where source and destination are states, and label is a letter. $A_1$ in Fig. [1] is a simple automaton. A word $u$ is accepted by an automaton if there exists a path from an initial state to a final state that follows transitions whose concatenated labels equal $u$. $A_1$ accepts $bb$, and refuses $aa$.

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1 However in some cases it uses NumPy and SciPy, Python libraries that are partially written in C/C++/Fortran for performances.
Actually, the theoretical foundations are more general. Labels may be chosen to be letters or $\varepsilon$ (the empty word, neutral for the concatenation), or words, or even tuples of labels (for instance to model transducers: automata with input and output). However, labels must belong to a monoid: they can be concatenated, concatenation is associative and has a neutral element.

A transition is spontaneous if it is labeled by $\varepsilon$. An automaton without spontaneous transitions is proper. $A_1$ is proper.

Automata can be equipped with weights (also called multiplicities): evaluating a word on an automaton gives more than yes/no, it provides a “score” (e.g., a probability). Weights along a path are multiplied, and weights between paths are added. For instance $A_2$ evaluates $bb$ as 3; path $(0,0,1)$ computes $1 \times 1$, and path $(0,1,1)$ computes $1 \times 2$. In fact $A_2$ computes the value of binary numbers written on $\{a, b\}$. Mathematically, the set of weights is said to be a semiring: a structure $(\mathbb{K}, +, 0, \cdot, 1)$ such that $(\mathbb{K}, +, 0)$ is a commutative monoid, $(\mathbb{K}, \cdot, 1)$ is a monoid, $\cdot$ distributes over $+$, and $0_K$ is an annihilator for $\cdot$: $\forall k \in \mathbb{K}, k \cdot 0_K = 0_K = 0_K \cdot k$.

1.3 Outline

Contributions. This paper presents a way to add dynamic polymorphism on a templated C++ library. This dispatching does not require arguments to be members of an OO hierarchy of classes; in a way, it lifts C++ static overloading and function templates into runtime polymorphism. Flexibility, and in particular support for an open world of types, is implemented using introspection, runtime code-generation, compilation and loading. We also introduce Value/ValueSet, a design that allows an efficient implementation of algebraic entities such as monoids, semirings, etc.

While this paper focuses on automata, the techniques may be applied in other domains where large structures depend on many small values, for instance image processing. However because we are particularly interested in adding runtime instantiation for templates, a C++-specific feature, and because the implementation uses so many C++ features, we do not think exposing our approach independently from this language would make any sense. We tried to stay away from technical issues, but it is quite impossible to do so without hiding critical components. Hence, the reader is expected to be comfortable with modern C++.

Outline. In Sect. we describe \texttt{vcsn:}, the base layer, a templated C++ library, and in particular the Value/ValueSet design. Sect. details how the second layer, \texttt{dyn:}, adds some runtime introspection, runtime polymorphism, and runtime instantiation. In Sect. we discuss some of the ideas and techniques that were used, what they make possible, and some benchmarks. Sect. is dedicated to previous and future works. Sect. concludes.
2 The Template-Based Library: vcsn:

The bottom layer of Vcsn is vcsn::, a heavily templated C++ library. It consists of a set of data structures—following a design which we call Value/ValueSet—and algorithms on these data structures.

2.1 Value/ValueSet

vcsn:: deals with a wide range of value types: from labels and weights to automata, rational expressions (aka regular expressions) and others. Labels and weights are typically small (Booleans, bytes, integers, etc.), while automata and expressions are large, possibly very large (hundreds of thousands of states).

A single C++ type may actually correspond to several algebraic structures. For instance, bool may model either \(B\), the traditional Booleans (where the addition is “or”, hence \(1+1=1\)), or the field \(F_2\) which corresponds to arithmetic modulo 2 (i.e., the addition is “xor”: \(1+1=0\)). As another example, int may be equipped with the traditional addition and multiplication, or min as an addition (\(\text{MAX\_INT}\) is its neutral) and + as multiplication (0 is its neutral)\(^2\).

Since native data types such as bool or int lead to several possible algebraic structures, they don’t suffice to model our weights. The traditional design would then introduce classes such as traditional_boolean with an attribute of type bool, and another f2_integer also with an attribute of type bool. However, this design does not scale in the case of stateful valuesets.

Consider the case of labels: they are always defined with respect to a specific alphabet; labels with invalid letters must be rejected. If we were to apply the straightforward design, the constructor of the labels would need an access to the alphabet, and possibly some other runtime parameters. Hence, a label as simple as a char would require an additional 4x or 8x payload penalty to carry around at least a pointer to its alphabet.

To address this issue we use the Value/ValueSet design, that goes somewhat backwards compared to OOP: traditional objects are split in value on the one hand, and operations on the other hand. The Values (such as bool or int) are “dumb”: they do not provide any operation, they cannot even print themselves. The ValueSets (such as b for \(B\) and f2 for \(F_2\), z for \(\mathbb{Z}\) and zmin for \(\mathbb{Z}\) with min and +) provide all the operations: construction (including validation), conversion, addition, multiplication, access to specific values (the neutrals), etc.

2.2 Concepts of vcsn::

In our design, types of automata are captured by two sets: the labelset is the set of the valid labels (e.g., \(\{a, b\}\): only letters, or \(\{a, b\}^*\): words of any length on \(\{a, b\}\)), and the weightset is the set of the valid weights (e.g., \(B\) for \(A_1\) and \(\mathbb{Z}\)

\(^2\) If \(A_2\) from Fig. 1 is interpreted with min and +, then \(bb\) is evaluated as \(0 = \text{min}(0 + 0, 0 + 2)\). More generally, \(A_2\) returns twice the number of a after the last b, or 0 if there is no b.
for $A_2$). A pair composed of a labelset $L$ and a weightset $W$ is named a context, and is denoted $L \rightarrow W$.

ValueSets in vcsn:: comply with a handful of concepts: WeightSet, LabelSet, ExpressionSet for rational expressions, PolynomialSet etc. We also provide a tupleset variadic class template that allows define Cartesian products of ValueSets. For instance, $F_2 \times \mathbb{Z}_{\min}$ is a valid WeightSet, and $\{a, b\} \times \{x, y, z\}^*$ models labels that are pairs whose first member is either an $a$ or a $b$, and whose second member is any string of $x, y$ and $z$.

C++ features an extremely powerful model of templates: classes and functions can depend on formal template parameters: compile-time meta-variables denoting types or values. Obviously a given template expects its actual template parameters to comply with some constraints, such as “supports an addition”, “is default constructible” and so forth. Introduced by the C++ Standard Template Library (STL), the C++ community names concepts these requirements on template parameters. Unfortunately C++ does not support concepts, yet. We will follow the syntax of the latest proposal for concept in C++ [30, 29].

The LabelSet, the set of valid labels, must be a subset of a monoid; for instance, given a letter type $A$, leterset$<$A$>$ denotes the set of single-letter labels, and wordset$<$A$>$ that of strings.

The theory requires weights to form a semiring. The corresponding concept in vcsn:: is WeightSet:

```cpp
template <typename T>
concept bool WeightSet() {
    using value_t = typename T::value_t;
    return requires(value_t a, value_t b) {
        equal_to(a, b) -> bool; less(a, b) -> bool;
        zero() -> value_t; one() -> value_t;
        add(a, b) -> value_t; mul(a, b) -> value_t;
        // ...
    };
}
```

The class template context aggregates a LabelSet and a WeightSet.

### 2.3 Conversions and Join

There exists a subtype relation between labelsets [10], denoted $\ll$. For instance, since a letter can be seen as a string, leterset$<$A$>$ $\ll$ wordset$<$A$>$. WeightSets also feature a subtype relation. For instance $\mathbb{N} \ll \mathbb{Z} \ll \mathbb{Q} \ll \mathbb{R}$.

Vcsn:: implements conversion routines to supertypes, for instance, to convert an automaton of type $\{a, b\} \rightarrow \mathbb{N}$ to an automaton of type $\{a, b, c\}^* \rightarrow \mathbb{Q}$.

As a more complex example, consider RatE $\{\{a, b\} \rightarrow \mathbb{Q}\}$, the set of rational expressions on letters $\{a, b\}$ with weights in $\mathbb{Q}$. Rational expressions with weights in $\mathbb{Z}$ can be converted as expressions with weights in $\mathbb{Q}$ (e.g., $3a^* \Rightarrow \frac{3}{2}a^*$), so RatE $\{\{a, b\} \rightarrow \mathbb{E}\} \ll$ RatE $\{\{a, b\} \rightarrow \mathbb{Q}\}$. Fractions can also been seen as expressions whose weights are fractions, e.g. $\frac{1}{2} \Rightarrow \frac{1}{2}\varepsilon$; hence $\mathbb{Q} \ll$ RatE $\{\{a, b\} \rightarrow \mathbb{Q}\}$. 

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Vcsn:: also provides routines to compute the smallest common supertype of two types, which we call the *join*. For instance, \( \text{Rat}E \left[ \{ a, b \} \to \mathbb{Q} \right] \) is the join of \( \text{Rat}E \left[ \{ a, b \} \to \mathbb{B} \right] \) and \( \mathbb{Q} \).

2.4 The Algorithms

With data structures on the one hand, and algorithms on the other hand, Vcsn:: is implemented like STL. Indeed, all the algorithms are templated, yet expect their arguments to implement the needed concepts. Many algorithms have a rather straightforward interface. For instance checking whether an automaton is proper (has no spontaneous transitions), or evaluating a word:

```cpp
template <typename Aut>
auto is_proper(const Aut& a) -> bool;
```

```cpp
template <typename Aut>
auto evaluate(const Aut& a, const word_t_of<Aut>& w) -> weight_t_of<Aut>;
```

where `word_t_of<Aut>` is the type of words corresponding to automata of type `Aut`, and likewise for `weight_t_of<Aut>`.

*Algorithms with Alternatives.* Some computations can be implemented by different algorithms, with different preconditions. For instance minimization (which consists in producing a smaller automaton) currently comes in three flavors:

```cpp
// a must be deterministic, its WeightSet must be Boolean.
template <typename Aut>
auto minimize_moore(const Aut& a) -> subset_automaton<Aut>;
```

```cpp
// The LabelSet of a must be free.
template <typename Aut>
auto minimize_signature(const Aut& a) -> subset_automaton<Aut>;
```

```cpp
// The LabelSet of a must be free.
template <typename Aut>
auto minimize_brzozowski(const Aut& a) -> brzozowski_automaton<Aut>;
```

where `subset_automaton` is a specific type of automaton whose states “remember” the states of the input automaton they correspond to. The `brzozowski_automaton` also maintains a connection with its input automaton, but the relationship is different.

*Value Parameters.* Some operations are templated by integers. Consider for instance an automaton of type \( \{ a, b \} \times \{ x, y, z \}^* \to \mathbb{Q} \): it has two tapes, one labeled with letters in \( \{ a, b \} \), and the second with words on \( \{ x, y, z \} \). The *focus* algorithm hides all the tapes except one. The type of the resulting automaton \( \{ a, b \} \to \mathbb{Q} \) or \( \{ x, y, z \}^* \to \mathbb{Q} \) therefore depends *statically* on the tape number: it is a (compile-time) template parameter, not a (runtime) function argument:

```cpp
template <unsigned Tape, typename Aut>
auto focus(const Aut& aut) -> focus_automaton<Tape, Aut>;
```
Variadic Functions. The synchronized product of automata is a binary, associative, operation. What it computes is irrelevant to this paper. However, much alike matrices addition, when chained, it is much more efficiently handled as a single variadic operation rather that repeated binary ones. Vcsn:: offers the product as a variadic function: it accepts any number of automata, besides, of heterogeneous type:

```
template <typename... Auts>
auto product(const Auts&... as) -> product_automaton<Auts...>;
```

To summarize, vcsn:: features algorithms that are alike but with different return types (minimization), algorithms whose return type is computed from those of the arguments (union), algorithms that statically depend on integers (focus), and variadic algorithms (product).

3 The Dynamically-Typed Library: dyn::

The vcsn:: library presented in Sect. 2 is a typical instance of a C++ template library: it is generic and efficient (it is on par with OpenFst [9]). But it falls short on the flexibility: if an object of an unexpected type is needed (e.g., an automaton is loaded from a file), the library throws an exception and the program terminates.

The purpose of dyn:: is to bring flexibility on top of vcsn::. This is achieved via type-erasure techniques, and some introspection support to provide rich runtime-type information —not to be confused with the C++ native Runtime-Type Information (RTTI) support.

3.1 Introspection: Signatures

To implement dynamic polymorphism we provide each type lifted in dyn:: with a unique key, its sname. Snames are strings that look like C++ types, e.g. "int" for int arguments, "const std::string" for const std::string etc. This is a lot like what the C++’s native RTTI provides via typeid::name(); however there is no guarantee on what typeid::name() actually returns, and anyway, in some cases we need to “lie” to get powerful interfaces between dyn:: and vcsn:: (see Sect. 3.8).

Because snames are used as keys in tables, they are internalized, i.e., we use Boost.Flyweight [31], an implementation of the Flyweight design pattern [12], to keep a single instance of each value. The main concern is not saving space, but having fast core operations: since every value is represented by a unique instance, comparisons and hashing are shallow as they are performed on the addresses.

The sname() function is a type traits [19], a classical C++ technique which allows to cope with pre-existing types that might not even be classes (e.g., int).

The Values do not need an sname, and actually, they cannot provide one: knowing that a weight is of type bool does not tell anything about its algebraic
nature (B or \( \mathbb{F}_2 \)). On the other hand, ValueSets have an sname (e.g., "b", "f2", or "letterset<char_letters>").

Note that \( \text{sname()} \), being based on traits, does not take any runtime function argument, it depends solely on its static template parameters. This is a key property for the registration process (Sect. 3.6).

3.2 Type Erasure

The \( \text{dyn::} \) layer relies on type erasure to store a \text{vcsn::} pair Value/ValueSet in a \( \text{dyn::} \)-\text{value} object. \(^3\)

```cpp
namespace dyn {
  // Type-erased Value/ValueSet.
  template <typename Tag>
  class value { public:
    template <typename ValueSet>
    value(const ValueSet& vs, const typename ValueSet::value_t& v)
      : self_(std::make_shared<model<ValueSet>>(vs, v)) {}
    // Runtime type of the effective ValueSet.
    auto vname() const -> symbol { return self_->vname(); }
    // Extract wrapped typed Value/ValueSet pair.
    template <typename ValueSet>
    const auto& as() const {
      return dynamic_cast<const model<ValueSet>&>(*this);
    }
  private:
    class base { public:
      virtual ~base() = default;
      virtual symbol vname() const = 0;
    };
    // Type-full ValueSet/Value pair.
    template <typename ValueSet>
    class model final : public base { public:
      using value_t = typename ValueSet::value_t;
      model(const ValueSet& vs, const value_t& v)
        : valueset_(vs), value_(v) {}
      auto vname() const override { return valueset_.sname(); }
      const auto& valueset() const { return valueset_; }
      auto value() const { return value_; }
    private:
  }
}
```

\(^3\) In order to keep the code snippet short and legible, we used the C++14 syntax which allows to leave the return type unspecified, to be deduced by the compiler.
There are several features of `dyn::value` that are worth being emphasized. First, the Value/ValueSet duality is fused: whereas in `vcsn::`, one needs a ValueSet (such as `letterset`) to manipulate Values (such as `char`), in `dyn::` “values” are complete and self-sufficient.

Second, users of `dyn::` are freed from memory management, as the Application Program Interface (API) relies on shared pointers. This applies for both human users, and possible layers built on top of `dyn::` (see Sect. 4.3).

Third, we emphasize a functional-style purity: the Value and ValueSet that `dyn::value` aggregates are immutable (`const`). The base class, `value<Tag>::base`, is a plain class: it is not templated. The `value<Tag>::model` class template generates its only derived classes. This hierarchy provides two services only: introspection via the `vname()` function, and type-recovery via `as()` (see Sect. 3.3).

In debug mode, our type-recovery system uses C++’s RTTI (`dynamic_cast`) to check for invalid conversions. However, in practice, `static_cast` suffices: we do not use multiple inheritance, and our introspection routines never allow a conversion with an invalid type.

### 3.3 Calling an Algorithm

As a running example, consider `evaluate`, the evaluation of a word by an automaton, which returns a weight. Obviously, incoming arguments must be converted from `dyn::` to `vcsn::`, and conversely for the result. This is ensured by another `evaluate` function, which we call the *static/dynamic bridge*, which uses the `as` functions for `dyn::` to `vcsn::` conversion, and the `weight` (i.e., `value<weight_tag>`) constructor for the converse:

```cpp
namespace dyn::detail {
    template <typename Aut, typename LabelSet>
    auto evaluate(dyn::automaton aut, dyn::label lbl) -> dyn::weight {
        const auto& a = aut->as<Aut>();
        const auto& l = lbl->as<LabelSet>().value();
        const auto& w = ::vcsn::evaluate(a, l);
        const auto& ws = a->context()->weightset();
        return {ws, w};
    }
}
```
The bridge is actually a template: it must be parameterized by the exact type of the wrapped automaton and wrapped label. If \texttt{dyn::evaluate} were to work for a single type of automaton, it would look as follows.

```cpp
namespace dyn {
    using automaton_t = mutable_automaton<context_t>;
    using labelset_t = labelset_t_of<context_t>;

    auto evaluate(automaton aut, label l) -> weight {
        return detail::evaluate<automaton_t, labelset_t>(aut, l);
    }
}
```

Of course it needs to accept any type of automaton and labelset. This is where registries come into play.

### 3.4 Querying Registries

The actual implementation of \texttt{dyn::evaluate} is:

```cpp
auto evaluate(automaton aut, label l) -> weight {
    auto& reg = detail::evaluate_registry();
    return reg.call(aut, l);
}
```

It uses a Meyers-style singleton [18] to get \texttt{evaluate}'s own registry:

```cpp
using evaluate_t = auto (automaton, label) -> weight;
static auto evaluate_registry() {
    static auto instance = registry<evaluate_t>("evaluate");
    return instance;
}
```

A key feature of a given bridge such as \texttt{dyn::detail::evaluate} is that its signature does not depend on template parameters: all its instances comply with the signature of \texttt{dyn::evaluate}, \texttt{evaluate_t}.

Each algorithm of \texttt{dyn::} is associated with a single registry. In case of overloading, there must be one registry per overload. For instance

```cpp
auto print(label l, std::ostream& o) -> std::ostream&;
auto print(weight w, std::ostream& o) -> std::ostream&;
```

are associated with two registries: \texttt{print_label} and \texttt{print_weight}.

The registries play the role of the tables: depending on runtime conditions, dispatch to a single function pointer, which is specific to the type of the arguments. The \texttt{reg.call} invocation forwards the arguments to this specific instance of the bridge, selected by the registry.
3.5 Registries

The registries are instances of a class template, `registry`, whose type parameter `Fun` denotes the type of the `dyn::` function such as `evaluate_t`.

template <typename Fun>
class registry { public:
    registry(const std::string& name) : name_(name) {} // Invoke the registered function for args.
    template <typename... Args>
    auto call(Args... args) {
        auto sig = vsignature(std::forward<Args>(args)...); // The signature.
        return call_sig(sig, std::forward<Args>(args)...); // Invoke the registered function for sig, passing the args.
    }
    template <typename... Args>
    auto call_sig(const signature& sig, Args&&... args) {
        auto bridge = get(sig); // Get the corresponding bridge instance.
        return bridge(std::forward<Args>(args)...); // Invoke it.
    }
    auto get(const signature& sig) { return map_.at(sig); } // Get or throw.
    auto set(const signature& sig, Fun fn) { map_[sig] = fn; } // Register.
private:
    std::string name_; // Function name (e.g., "evaluate").
    std::map<signature, Fun*> map_; // Signature -> bridge.
};

To summarize, the sequence of events (see Fig. 2) when invoking `dyn::evaluate` on an automaton of type `mutable_automaton<letterset<char_letters>, b>` and a word of type `wordset<char_letters>` (abbreviated `aut_t` and `ls_t`) is:

- user calls `dyn::evaluate(da, dl)` with a `dyn::automaton` and a `dyn::label`;
- `dyn::evaluate` invokes `evaluate_registry` to obtain `reg`, the corresponding `registry` object;
- `reg.call(da, dl)` is invoked;
  - `call` uses `vsignature` to collect the argument vnames into `sig`;
  - `reg.call_sig(sig, da, dl)` is invoked;
    - it uses `sig` to get `bridge`, an instance of `detail::evaluate` parameterized by `sig`;
    - `bridge(da, dl)` is invoked;
      - `bridge` calls `da.as<aut_t>()` to extract `a`, (`a aut_t`) from `da`;
      - it extracts `l`, a `std::string`, from `dl`;
      - it calls `vcsn::evaluate(a, l)`;
      - `vcsn::evaluate` evaluates the word;
      - it returns a weight (`a bool`);
Fig. 2. Sequence diagram of `dyn::evaluate(a1, l1)`, where `da` is a `dyn::automaton` and `dl` a `dyn::label`.

- bridge receives this `vcsn::weight` in `w`;
- it gets `ws` (vcsn::b), the corresponding weightset, from `a`;
- it calls `dyn::make_weight` to wrap `ws` and `w` into a `dyn::weight`;
- it returns this `dyn::weight`;
- the bridge returns this `dyn::weight`;
- `reg.call_sig` returns this `dyn::weight`;
- `reg.call` returns this `dyn::weight`;
- `dyn::evaluate` returns this `dyn::weight` to the user.

That concludes the description of the events involved in a `dyn::` invocation. We now explain how the registries are initialized.

### 3.6 Filling Registries

In Vcsn, some “contexts” have been elected to be “builtins”, i.e., they are pre-compiled. Examples of such contexts are \( \text{char} \to \mathbb{B} \), \( \text{char}^* \to \mathbb{B} \), \( \text{char} \to \mathbb{Z} \) ... Each of these contexts is compiled as a shared library. This shared library has a static variable `registered` whose initialization calls a function which all registers the needed functions. For instance, for \( \text{char} \to \mathbb{B} \):

```cpp
using ctx = context<letterset<char_letters>, b>;
static bool registered = register_functions<ctx>();
```

with:
template <typename Ctx>
auto register_functions() {
    using aut_t = mutable_automaton<Ctx>;
    using wordset_t = wordset_t_of<Ctx>;
    // ...
    evaluate_registry().set(ssignature<aut_t, wordset_t>(),
        detail::evaluate<aut_t, wordset_t>());
    // ...
    return true;
}

Classical C++ meta-programming techniques such as std::enable_if are used to instantiate only algorithms whose preconditions are satisfied.

There is one issue, however, that this approach does not cover: the set of possible signatures is not closed. Consider for instance product: the arguments can be of any type! Hence, one cannot “precompile” all its possible instantiations. Code generation and dynamic shared-object loading allow to address this issue.

3.7 Code Generation

Our signatures are quite heavy-weight, and look like C++ types. They can be parsed to generate C++ code.

Concretely, the registry::get function (see Sect. 3.5) is a little more involved:

```cpp
auto get(const signature& sig) {
    if (!exists(sig))
        vcsn::dyn::instantiate(name_, sig);
    return map_.at(sig);
}
```

The instantiate function requests the instantiation of the algorithm named name_ (e.g., "evaluate") for the given signature. To do so, it generates the following piece of code:

```cpp
using t0_t = vcsn::mutable_automaton<vcsn::context<
    vcsn::letterset<vcsn::char_letters>, vcsn::b>>;
using t1_t = vcsn::wordset<vcsn::char_letters>;

auto sig = ssignature<t0_t, t1_t>();
auto fun = vcsn::dyn::detail::evaluate<t0_t, t1_t>;
static bool r = vcsn::dyn::detail::evaluate_registry().set(sig, fun);
```

Then instantiate calls the compiler and linker to produce a shared-object, which it loads via dlopen. The dynamic loader invokes the initialization of the shared-object, i.e., initializes the r variable, which registers this specific bridge in the map_ member. Finally get fetches the result in map_.

If the compilation failed, either for good reasons (e.g., failed preconditions) or bad one (bugs), instantiate throws an exception which is caught by the

---

4 It cannot return the function, for reasons explained below.
registry to improve the error message. First, it looks in the compilation log for “static assertion failed” messages, which is the sign that preconditions enforced by `static_assert` were invalidated. If found, this information is kept; other errors are discarded. Then it appends the failed signature, followed by the known ones, and finally it provides the compiler command line, to aid debugging.

If, for instance, you were to evaluate a word on an automaton labeled with words (`evaluate` requires labels to be letters), the system would produce the following error message:

```
RuntimeError: evaluate: requires a free labelset
failed signature:
  mutable_automaton<wordset<char_letters>, b>, wordset<char_letters>
available versions:
  mutable_automaton<letterset<char_letters>, b>, wordset<char_letters>
  mutable_automaton<letterset<char_letters>, q>, wordset<char_letters>
[
failed command:
  LC_ALL=C ccache g++-4.9 -std=c++14 -fPIC `base.cc` -c -o `base.pid.o`
with base = `root/algos/evaluate/sig`, root = `$/HOME/.vcsn/plugins`, and sig = `mutable_automaton<wordset<char_letters>, b>, wordset<char_letters>`.]
```

The algorithm is compiled only once per session: the registry will not compile it again. To amortize the cost of compilation between sessions, we use `ccache`, a compiler cache for C and C++: only the first invocation of a non precompiled algorithm incurs the cost of runtime compilation.

Written naively, runtime code generation, compilation, linking and loading is exposed to race conditions: (i) two processes could be generating the same file (in which case we’d get two copies intertwined together in the same file, hence a compiler error), or (ii) could compile at the same time (causing the compiler to generate garbled object file, hence a linker error), or (iii) could link at the same time (resulting in a broken shared-object, hence a crash).

Race conditions might seem unlikely: they require the same user to request the same algorithm on the same signature several times, concurrently. However, two typical scenarios are exposed to such problems. One is when students use the web interface to Vcsn5: they all run under the same identity, and (hopefully) all run the same requests roughly at the same time: those from the assignment. The other is the test suite: it runs tests in parallel.

To address these issues we include the `pid`, the process identification number, in the file names. However, doing it blindly would void the interest of `ccache`, so in step (i), once the C++ file is generated, it is renamed atomically to a name independent of `pid`. Steps (ii) and (iii) do produce `pid`’d files; afterwards the shared-object is renamed atomically to its final name, before calling `dlopen`.

### 3.8 Customized Signatures

Most algorithms in `vcsn::` have a signature interfaced straightforwardly in `dyn::`:

5 Vcsn on-line, [http://vcsn-sandbox.lrde.epita.fr/](http://vcsn-sandbox.lrde.epita.fr/)
However in some cases, `dyn::` allows to do much better than mocking `vcsn::`.

**Algorithms with Alternatives.** `vcsn::` features several minimization algorithms, producing automata of different types, see Sect. 2.4 so they must be different functions. In `vcsn::` all these different automaton types are wrapped into the unique `dyn::automaton` type, so these functions can merged into a single one, with an additional argument to select the chosen algorithm. We can even do better, and provide an "auto" algorithm selector that chooses the best fit, using techniques such as `std::enable_if` to select the eligible algorithms.

**Binary Operations.** As a design decision, `vcsn::` is picky about types. For instance one cannot mix weights from $\mathbb{N}$ with weights from $\mathbb{Z}$. In `dyn::`, however, we introduce such automatic conversions. This is done in the bridges:

```cpp
template<typename WS1, typename WS2>
auto sum_weight(dyn::weight lhs, dyn::weight rhs) {
    // Unwrap the dyn::weights.
    const auto& l = lhs->as<WS1>();
    const auto& r = rhs->as<WS2>();
    auto ws = join(l.weightset(), r.weightset()); // Smallest common supertype.
    // Convert the input values.
    auto lr = ws.conv(l.weightset(), l.weight());
    auto rr = ws.conv(r.weightset(), r.weight());
    // Compute the result and wrap it into a dyn::weight.
    return make_weight(rs, vcsn::sum(rs, lr, rr));
}
```

**Depending on Runtime Values.** Applied to a multiple-tape automaton, `focus` hides all its tapes but one. Obviously, the resulting automaton type depends on a value (the tape number), not a type (unsigned). Rather than turning the existing system, based on types, into something more complex, we wrap values into types: when `dyn::focus` is passed 2, it pretends it was actually passed an argument whose type is `std::integral_constant<unsigned, 2>`. However, since we need the bridges to all have the same signature, `std::integral_constant<unsigned, 2>` cannot appear in their type.

To this end we introduce `vcsn::integral_constant`, a simple class that stores the signature it must pretend to have ("std::integral_constant<unsigned, 2>").

To summarize `dyn::focus` is:

```cpp
auto focus(automaton& aut, unsigned tape) -> dyn::automaton {
    auto t = integral_constant("std::integral_constant<unsigned, " + std::to_string(tape) + "]");
    return detail::focus_registry().call(aut, t);
}
```
and the bridge:

```cpp
template <typename Aut, typename Tape>
auto focus(automaton aut, integral_constant) {
    auto& a = aut->as<Aut>();
    return make_automaton(vcsn::focus<Tape::value>(a));
}
```

**Variadic Functions.** Because it accepts any number of automata as argument, the natural signature for a product in `dyn::` uses a vector of automata:

```cpp
auto product(const std::vector<automaton>& auts) -> automaton {
    return detail::product_vector_registry().call_variadic(auts);
}
```

This function invokes a different `call` function from the registry which, instead of putting `std::vector<automaton>` in the signature, queries each member of the vector for its signature, and collects them in a single one, used as key:

```cpp
template <typename T>
auto call_variadic(const std::vector<T>& ts) {
    signature sig;
    for (const auto& t: ts)
        sig.emplace_back(vname(t));
    return call_sig(sig, ts);
}
```

This final call ensures that the template parameters of the bridge will be the exact types of the input automata, and its (runtime) argument will be a vector of `dyn::automaton`. Using C++14 techniques, it unpacks the vector into a variadic call on `vcsn::` automata.

```cpp
template <typename... Auts>
auto product_vector(const std::vector<automaton>& auts) {
    return product_<Auts...>(auts, std::make_index_sequence<sizeof...(Auts)>{});
}
```

```cpp
template <typename... Auts, size_t... I>
auto product_<(typename... Auts, size_t... I)>
    (const std::vector<automaton>& auts, std::index_sequence<I...>) { 
    return make_automaton(vcsn::product(auts[I]->as<Auts>()...));
}
```

### 3.9 Deserialization of Contexts

The `dyn::` library is therefore able to instantiate algorithms on the fly, simply by asking existing objects (typically `context` instances) for their type. Sometimes, there is no object to start from, e.g., when loading a file.

The `make_context` function instantiates contexts: from specification strings such as "lal_char(abc), b" (or "context<letterset<char_letters(abc)>, b>", they are synonymous in Vcsn) it builds the actual C++ objects they denote. This

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is very different from the previous cases where registries depend on signatures (i.e., types) to dispatch their calls; here there is a single signature, \((\text{std::string})\), what changes is the value of that string.

The `make_context` function works in two steps: code generation (to support this specific type of contexts), and object instantiation (to instantiate it with the appropriate runtime values, here "abc").

```cpp
auto make_context(const std::string& spec) -> dyn::context {
    auto& reg = detail::make_context_registry();
    auto sname = sname_normalized(spec);
    auto sig = signature{sname};
    if (!reg.exists(sig)) vcsn::dyn::instantiate_context(sname);
    auto vname = vname_normalized(spec);
    return reg.call_sig(sig, vname);
}
```

**Code Generation.** The `spec` string is parsed, and pretty-printed to a canonical form, without runtimes values (e.g., "context<letterset<char_letters>, b>"). This is used to forge the signature, instead of the useless "(std::string)". We may now query the corresponding registry to check whether the function already exists, and request its generation if needed.

Instead of instantiating a single algorithm (`instantiate("make_context", sig)`), we “instantiate the context” (`instantiate_context(sname)`): we compile the same set of signatures of functions that were selected for the precompiled “builtins”.

This way, most functions are readily available when a context is first used.

**Context Instantiation.** The registry (see Sect. 3.5) is used to select the bridge of matching `sig`, passing it `vname` as argument: the normalized specification with the runtime values (such as `abc`). In turn the bridge calls `vcsn::make_context`:

```cpp
template <typename Ctx>
auto make_context(const std::string& vname) -> Ctx {
    std::istringstream is{vname}; return Ctx::make(is);
}
```

All the ValueSets implement the `make` static function that allows to deserialize them. For instance, in the case of `context`:

```cpp
static auto context::make(std::istream& is) {
    eat(is, "context<"); auto ls = labelset_t::make(is); eat(is, ",");
    auto ws = weightset_t::make(is); eat(is, ">");
    return context{ls, ws};
}
```

4 Discussion

In this section, we discuss the strengths and weaknesses of our proposal. One of the goals of `dyn` was to make easier the binding to dynamic languages, and we expose our experience with Python. The costs registry-based polymorphical calls are evaluated, and we briefly discuss the importance of C++11 in this framework.
4.1 The Values of Value/ValueSet

The Value/ValueSet design is the backbone of the Vcsn platform. It replaces the “Element/MetaElement” design that was used in Vaucanson 1, the first incarnation of the Vaucanson project. The purpose of Element/MetaElement is to bind together the elements (say a bool value) with its MetaElement: the algebraic structure to which it belongs (say the semiring B). The foremost advantage of the approach is that the C++ operators could be overloaded: e + f was using the MetaElement to get the proper implementation of the addition. However, in the long run, this way of structuring the library proved to be cumbersome, and considerably hindered the development. The library was way too complex even for seasoned C++ programmers.

Value/ValueSet has a similar goal, however Values and ValueSets are never bound together at the vcsn:: level. In turn, this implies that operators cannot be overloaded, and code such as sum = ws.add(sum, ws.mul(lhs, rhs)) — where ws is the ValueSet of sum, lhs and rhs — is quite frequent in the library. However, it turns out to be more pleasant than relying on the operators: first it is much easier to follow the function calls (they are scoped by the ValueSet while C++ operators can be defined as member or non-member functions), second the resulting interface is more consistent: all the operations are named, not just some of them.

In dyn::, since Value and ValueSet are reunited, we can support operators. Operators are offered to the end users as a nice API, but avoided in the implementation layers.

ValueSets share similarities with STL: don’t put the algorithms in the Values, keep them outside. However, the core algorithms thanks to which a Value implements a concept are actually grouped together by the ValueSet.

Because ValueSets enforce consistency, in Vcsn it was surprisingly easy to use some ValueSets in unexpected ways. For instance, rational expressions can be used where weights are expected, because the ExpressionSet concept is a superconcept of WeightSet. Conversely, because we did not follow this guideline for our implementation of automata, we can’t use them as weights.

4.2 Benefits of dyn::

It is remarkable, but not unexpected, that objects and functions in dyn:: correspond to concepts (in the C++ sense) of vcsn::: WeightSets become dyn::weight, the different types of automaton (mutable_automaton<Ctx>, subset_automaton<Aut>, etc.) are mapped to dyn::automaton, etc. Even different algorithms that realize a common specification (minimize_moore<Aut>, minimize_signature<Aut>, etc.) — which can be seen as several functions corresponding to a single concept— map to a single function.

The dyn:: API therefore is much smaller, much simpler to use that vcsn::: it was designed primarily for the end users which are not experienced C++ programmers. However, the developers largely benefited from it. We cannot over-
state how the introduction of dyn:: simplified the development of the platform, especially wrt Quality Assurance (QA).

Because it is very easy to create a dedicated binary for each algorithm (e.g., vcsn-evaluate), the first generation of the test suite was based on simple shell-scripts checking input/output combinations. This contrasts with the need to instantiate one program for each template parameters set, which requires Makefile machinery, etc.

Because all the tests are on top of dyn::, the test cases are perfectly factored. Testing an algorithm for a specific type of automaton always requires some basic routines on this automaton type (e.g., input/output). In VAUCANSON 1 these routines were compiled for each binary test case. Thanks to dyn:: they are shared between tests and their compilation is factored.

Before the advent of dyn:: our development cycle was the usual “edit-compile-test”, where “compile” means “compile the library”, which may count in tens of minutes. This is especially painful when a single change in a header causes recompilations of components other than the tested one. Daredevils may recompile just the one shared-object corresponding to the component they are testing, but that’s tricky and dangerous. With the introduction of dyn::, since it always recompiles the non-built-in vcsn:: algorithms, the development became “edit-test”, and dyn:: deals with maintenance issues: if an algorithm needs to be recompiled, it will be, and otherwise ccache avoids compilation.

Another major benefit from dyn:: is that binding to other environments, such as Python, becomes (almost) trivial.

4.3 Binding a Templated C++ Library to Python

Binding a templated C++ library such as vcsn:: in a dynamic language (e.g., Python) has always been hard. Tools such as SWIG [5, 8] are available, however, they have a hard time coping with the whole syntax of C++ —let alone with its recent evolutions (e.g., C++14)— and more importantly, cannot offer an integration as smooth as what dyn:: provides on top of vcsn::.

Sitting SWIG on dyn:: would be much easier, but we chose Boost.Python, a simple means to bind C++ into Python [1].

The dyn:: API is an collection of free standing functions; it is not OO to remain extensible: new function members cannot be added at runtime in C++. Since Python supports it, our Python binding is OO. Evaluation in dyn:: is evaluate(aut, word), in Python it is aut.evaluate(word), or even aut(word).

Operators get their natural infix syntax: a1.add(a2) in dyn:: is a1 + a2 in Python. We simulate expression templates [32] and bind a1 & a2 & a3 & a4 in Python into a single call to the variadic function dyn::product (see Sect. 3.8).

The second generation of the test suite was written as Python scripts instead of shell-scripts calling Vcsn binaries. This way the Vcsn framework is loaded only once per Python script, instead of once per component of a test-case! Besides, since these processes were communicating via files or pipes, values were continuously serialized and deserialized.
| empty  | vcsn | virt | dyn | Python | Storage | Cast         |
|--------|------|------|-----|--------|---------|-------------|
| 0.023ns| 0.023ns| 1.67ns| 127ns | 371ns  | map     | dynamic     |
| 0.023ns| 110ns  | 351ns | 74ns  | 248ns  | unordered_map | static |

Table 1. Average duration of one call. We kept the fastest runs out of $10 \times 3$, one run making a loop of 1M calls. In the first row, the registry uses a std::map and dyn:: uses a dynamic_cast, as opposed to a static_cast in the next row. In the last row we used std::unordered_map and static_cast. 'empty': no algorithm is run at all, to measure the overhead of the benchmarking tool and the accuracy of the system clock; 'vcsn': vcsn::is_proper is used; 'virt': a simple OOP hierarchy calls vcsn::is_proper via virtual; 'dyn': dyn::is_proper; 'Python': aut::is_proper().

Python was chosen especially because of IPython [22], which offers a rich graphical interactive environment. Thanks to a very thin additional layer, users can run commands on automata and see a graphical rendering. There are even dedicated widgets for interactive edition of automata. This environment was used successfully in three batches of practical sessions with students. It is available online.

4.4 The Cost of dyn:: Polymorphic Calls

Extreme efficiency of the bridge between vcsn:: and dyn:: has little importance: Vcsn was designed so that algorithms be written in vcsn::, not dyn::. Writing CPU intensive loops in dyn:: is not a realistic scenario. However, we performed the following measurements to evaluate its cost.

The first series uses the is_proper algorithm: check whether an automaton has spontaneous transitions. What is specific about this algorithm is that automata of the type used in the benchmark cannot have spontaneous transitions, so the vcsn:: implementation is straightforward:

```cpp
template <typename Aut>
constexpr std::enable_if_t<!labelset_t_of<Aut>::has_one(), bool>
is_proper_(const Aut&) { return true; }
```

Therefore, is_proper is well suited to measure the cost of the dynamic dispatch only: the algorithm itself is next to empty. We also used our benchmarking procedure on a empty statement. The automaton type is “builtin”: there is no code generation needed.

Table 1 presents the results, performed on a MacBook Pro, OS X 10.9.5, Intel Core i7 2.9GHz, 8GB of RAM, using Clang 3.5, with ‘-DNDEBUG -O3’. The C++ measurements used std::chrono::steady_clock, the Python measurements used timeit.repeat. One run is a loop of one million calls, the benching script returns the best out of three runs, and we kept the best out of ten runs of the script. As expected, the compiler optimizes out the vcsn:: calls: care was taken so that in that precise case, no code is run. An optimized dyn:: call is roughly 45x slower.
than a virtual call, and Boost.Python/Python, in the best case, makes it 150x slower.

Highlighted this way, the differences are large. However, they are imperceptible in typical uses cases. Table 2 covers five typical algorithms of automata theory, related to the Kleene theorem, on a very moderate input: starting from the expression $[abc]*[abc]^*$, build the Thompson automaton, eliminate the spontaneous transitions (proper), determinize it, minimize it, and convert the resulting (one state!) automaton into an expression ($[abc]^*$). Results show that even on very small inputs the cost of dyn:: calls is in the order of the variability of the measurements (as shown by the fact that virt is faster than vcsn::): one call to the whole sequence lasts for 112 $\mu$s in vcsn::, 121 $\mu$s in Python, to be compared to the 380 ms taken by dot [13] to convert this one-state automaton into SVG—not even counting its rendering.

| algorithm       | vcsn | virt | dyn  | Python |
|-----------------|------|------|------|--------|
| thompson        | 8.1 $\mu$s | 8.7 $\mu$s | 8.9 $\mu$s | 9.7 $\mu$s |
| proper          | 51.8 $\mu$s | 49.8 $\mu$s | 50.6 $\mu$s | 52.4 $\mu$s |
| determinize     | 19.0 $\mu$s | 19.3 $\mu$s | 19.7 $\mu$s | 20.9 $\mu$s |
| minimize        | 27.6 $\mu$s | 27.7 $\mu$s | 27.8 $\mu$s | 29.5 $\mu$s |
| to_expression   | 6.6 $\mu$s | 6.9 $\mu$s | 7.7 $\mu$s | 8.9 $\mu$s |
| Total           | 113.1 $\mu$s | 112.4 $\mu$s | 114.7 $\mu$s | 121.5 $\mu$s |

Table 2. Average duration of one call, by keeping the fastest runs out of $10 \times 3$, loops of 100k calls.

4.5 Relevance of C++11

C++11 made the development much easier than C++98.

C++11 plays an important role in the implementation details. For instance the registries use variadic templates and perfect forwarding in registry::call, once to compute the signature of the actual arguments, and then to forward these arguments to the selected bridge. The possibility to use decltype to deduce the return-type of a function call proved to be extremely useful.

But C++11 also shows in the public API, notably the shared pointers in dyn::. Actually, vcsn:: also uses shared pointers extensively for automata. In particular, some automata (such as brzozowski_automaton or subset_automaton) keep track of automata they were computed from to provide richer metadata, such as the semantics of the states. A call to vcsn::strip removes the decorator and keep only the “naked” automaton. This would not have been possible had automata been plain values rather than shared pointers.
5 Other Works

Our proposal involves components that were already described in publications. However, most of the existing work is on language design, rather than library design.

5.1 Previous Work

“Static vs. dynamic typing”, a duality that often splits programming language communities into opponents. Some efforts were conducted to bring both together into a single language [17, 6]. Our approach does not involve changing the language we use, but rather see how some of its features can be combined together in order to provide some of the benefits of dynamic typing on top of a statically typed API.

The idea of treating polymorphically C++ classes unrelated by inheritance and/or having no virtual methods is not new. This is “external polymorphism”, introduced twenty years go by Cleeland et al. [7]. However it seems to be designed to cope with incompatible components, say from different vendors. We propose to ground the design of the library on this idea, and to rely on introspection to be able to generate new components.

The core of the Olena image processing project is a C++ highly templated library. They explored very soon the idea of developing a dynamic layout on top of it [11]. However, while small scale experiments were achieved [25], it never worked sufficiently well to be integrated in the project.

Our implementation of registry is very similar to “Object Factories” [2, Chap. 8], an implementation of the Abstract Factories [12] tailored for C++.

Our bridges implement multiple-dispatch, “the selection of a function to be invoked based on the dynamic type of two or more arguments” [23, 24]. Compared to the current proposals for multi-methods in C++, do not require the dispatching to be performed on members of a classical OO hierarchy. We also use a rich introspection system to support code generation, and therefore a more costly dispatch mechanism. However, if performances were an issue, it would be interesting to rely on similar dispatching techniques for existing functions.

5.2 Future Works

Tuning the Compiler. The availability of the compiler at runtime provides us with different ways of exploiting it. As of today, compiling a full context takes about 85s with ‘-O3 -g’, 51s with ‘-O3’, 32s with ‘-O0 -g’, and 21s with ‘-O0’ (when ccache has a miss, otherwise consistently 0.5 s). Compiling a specific algorithm with the same options takes 30s, 23s, 22s, and 16s. Therefore it would be interesting to first compile without any optimization enabled, and then decide whether to run an optimized compilation, possibly in background, when the algorithm is deemed “hot”. We can also enable profile-guided optimizations. This is similar to the adaptive (re)compilation, pioneered by the Self programming language [15].
Better Domain Specific Syntax. The current syntax of the runtime type descriptors (snames) is neither suitable for the human, nor directly exploitable as C++. Because the user is actually exposed to it, we plan to move to a more natural syntax, such as \texttt{char -> B}, but this syntax must be extensible \textit{at runtime} to support user-defined ValueSets.

6 Conclusion

C++ is a widely used language to design generic and efficient libraries crunching large data set: image/signal processing, machine learning, computational linguistics, etc. Interactive environments with the typical read-eval-print loop provide a rich way to experiment with data and algorithms. We presented a means to build such a dynamic environment, with an open set of types, on top of a statically typed, closed world, C++ library. To achieve this goal, we need rich runtime introspection, under the form of complete type names. Collections of these type names form signatures which are used as keys in associative containers to get the corresponding function template instance. When the function is unknown, the type names are rich enough to generate C++ code instantiate the missing signature, and load it in the associative container via \texttt{dlopen}. We have shown how the dispatching system supports multi-methods, but also how it permits the definition of a simple and unified API on top of multiple function overloads, including variadic support. Building an interactive environment for experiments, say using Python/IPython, becomes extremely easy, the end user being completely shielded from template instantiation issues. This framework was detailed in the case of an environment dedicated to automata, however it is applicable elsewhere, provided a similar runtime type introspection system is implemented.

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