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A C++ Template-Based Reinforcement Learning Library:
Fitting the Code to the Mathematics

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Abstract
This paper introduces the rlLib as an original C++ template-based library oriented toward value
function estimation. Generic programming is promoted here as a way of having a good fit between
the mathematics of reinforcement learning and their implementation in a library. The main concepts
of rlLib are presented, as well as a short example.

Keywords: reinforcement learning, C++, generic programming

1. C++ Genericity for Fitting the Mathematics of Reinforcement Learning

Reinforcement learning (RL) is a field of machine learning that benefits from a rigorous mathemati-
cal formalism, as shown for example by Bertsekas (1995). Although this formalism is well accepted
in the field, its translation into efficient computer science tools has surprisingly not led to any stan-
dard yet, as mentioned by Kovacs and Egginton (2011). The claim of this paper is that generici-
ness enables a natural expression of the mathematics of RL. The rlLib (2011) library implements this
idea in the C++ language, where genericity relies on templates. Templates automate the re-writing
of some generic code involving user types, offering a strong type checking at compile time that
improves the code safety.

Using the rlLib templates requires that the user-defined types fit some documented concepts.
For example, some class C defining an agent should be designed so that C::state_type is the type
used for the states, C::action_type is the type used for the actions, and the method C::action_type
policy(const C::state_type& s) const is implemented, in order to compute the action to be
performed in a given state. This concept definition specifies what is required for an agent mathemati-
cally. Note that C does not need to inherit from any kind of abstract rl::Agent class to be used
by the rlLib tools. It can be directly provided as a type argument to any rlLib template requiring
an argument fitting the concept of an agent, so that the re-written code actually compiles.

2. A Short Example

Let us consider the following toy-example. The state space contains values from 0 to 9, and actions
consist in increasing or decreasing the value. When the value gets out of bounds, a reward is returned

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(-1 for bound 0, 1 for bound 9). Otherwise, a null reward is returned. Let us define this problem and run Sarsa. First, a simulator class fitting the concept Simulator described in the documentation is needed.

```cpp
class Sim { // Our simulator class. No inheritance required.
private:
    int current; double r;
public:
    typedef int phase_type ;
    typedef int observation_type ;
    typedef enum {up, down} action_type ;
    typedef double reward_type ;

    Sim(void) : current(0), r(0) {}
    void setPhase(const phase_type &s) {current = s%10;}
    const observation_type& sense(void) const {return current;}
    reward_type reward(void) const {return r;}
    void timeStep(const action_type &a) {
        if(a == up) current++; else current--;
        if(current < 0) r=-1; else if(current > 9) r=1; else r=0;
        if(r != 0) throw rl::exception::Terminal("Out of range");
    }
};
```

Following the concept requirements, the class Sim naturally implements a sensor method sense that provides an observation from the current phase of the controlled dynamical system, and a method timeStep that computes a transition consecutive to some action. Note the use of exceptions for terminal states. For the sake of simplicity in further code, the following is added.

```cpp
typedef Sim::phase_type S;
typedef Sim::action_type A;
typedef rl::Iterator<A,Sim::up,Sim::down> Aenum; // enumerate all actions.
typedef rl::SA<A> SA;
typedef rl::sa::Transition<S,A,double> Transition ; // i.e., (s,a,r,s',a')
```

As Sarsa computes some Q-values, a structure is needed to store these values. A \(10 \times 2\) array could be used, but our library is oriented toward value function estimation. It means that the Q-function computed by Sarsa is an element taken in some parametrized set of functions from \(S \times A\) to \(\mathbb{R}\). The parameter used is a vector. Such Q-function fits the concept of DerivableArchitecture. Let us here consider a tabular representation of \(Q\): a \(|S| \times |A| = 20\) array is actually implemented, but it is viewed as some particular case of parametrized function (there is one dimension in the parameter vector for each Q-value in the array, that is, the parameter vector is the array). This leads to the following definition of \(Q\). The explicit definition of the gradient of \(Q\) according to the parameter is required.

```cpp
class Q { // Tabular representation of Q (theta contains the Q[s,a]).
public:
    typedef S state_type ;
    typedef A action_type ;
    typedef SA input_type ;
    typedef Transition transition_type ;
    typedef gsl_vector* param_type ;

    param_type newParameterInstance(void) const {
        return gsl_vector_alloc(20); // 20 = |S|*|A|
    }

    output_type operator()(const param_type theta ,
                            state_type s, action_type a) const {
        return gsl_vector_get(theta,2*s+a); // return the value q(theta(s,a)).
    }

    void gradient(const param_type theta ,
                  state_type s, action_type a ,
                  param_type grad) const {
```

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The simulator and the parametrized Q-function are the only classes to be defined, since they are problem-dependent. From these types, the Sarsa algorithm can be easily implemented from rllib templates, as well as different kinds of agents. Here, learning is performed by an ε-greedy agent, while testing is executed by a greedy agent.

```cpp
class Param {
public:
    static double gamma(void) { return .99; }
    static double alpha(void) { return .05; }
    static double epsilon(void) { return 0.2; }
};
typedef rllib::sa::SARSA<Q, Param> Critic;
typedef rllib::sa::ArgmaxFromIteration<Critic, Aenum> ArgmaxCritic;
typedef rllib::agent::Greedy<ArgmaxCritic> TestAgent;
typedef rllib::agent::online::EpsilonGreedy<ArgmaxCritic, Aenum, Param> LearnAgent;
```

The rllib expresses that Sarsa provides a critic, offering a Q-function. As actions are discrete, the best action (i.e., \( \text{argmax}_{a \in A} Q(s, a) \)) can be found by considering all the actions sequentially. This is what ArgmaxCritic offers thanks to the action enumerator Aenum, in order to define greedy and ε-greedy agents. The main function then only consists in running episodes with the appropriate agents.

```cpp
int main(int argc, char* argv[]) {
    Sim simulator; // This is what the agent controls.
    Transition transition; // This is some s, a, r, s', a' data.
    ArgmaxCritic critic; // This computes Q and argmax_a Q(s, a).
    LearnAgent learner(critic); // SARSA uses this agent to learn the policy.
    TestAgent tester(critic); // This behaves according to the critic.
    A a; // Some action.
    S s; // Some state.
    int episode, length, step = 0;

    for(episode = 0; episode < 10000; ++episode) { // Learning phase
        rllib::episode::sa::run_and_learn(simulator, learner, transition, 0, length);
    }
    try { // Test phase
        simulator.setPhase(0);
        while(true) {
            s = simulator.sense(); a = tester.policy(s);
            step++; simulator.timeStep(a);
        }
    } catch(rllib::exception::Terminal e) {
        std::cout << step << "steps."
    }
    return 0; // the message printed is '10 steps.'
}
```

### 3. Features of the Library

Using the library requires to define the features that are specific to the problem (the simulator and the Q-function architecture in our example) from scratch, but with the help of concepts. Then, the specific features can be handled by generic code provided by the library to implement RL techniques with value function estimation.
Currently, Q-learning, Sarss, KTD-Q, LSTD, and policy iteration are available, as well as a multi-layer perceptron architecture. Moreover, some benchmark problems (i.e., simulators) are also provided: the mountain car, the cliff walking, the inverted pendulum and the Boyan chain. Extending the library with new algorithms is allowed, since it consists in defining new templates. This is a bit more technical than only using the existing algorithms, but the structure of existing concepts helps, since it reflects the mathematics of RL. For example, concepts like Feature, for linear approaches mainly (i.e., \( Q(s, a) = \theta^T \phi(s, a) \)) and Architecture (i.e., \( Q(s, a) = f_\theta(s, a) \) for more general approximation) orient the design toward functional approaches of RL. The algorithms implemented so far rely on the GNU Scientific Library (see GSL, 2011) for linear algebra computation, so the GPL licence of GSL propagates to the rllib.

4. Conclusion

The rllib relies only on the C++ standard and the availability of the GSL on the system. It offers state-action function approximation tools for applying RL to real problems, as well as a design that fits the mathematics. The latter allows for extensions, but is also compliant with pedagogical purpose. The design of the rllib aims at allowing the user to build (using C++ programming) its own experiment, using several algorithms, several agents, on-line or batch learning, and so on. Actually, the difficult part of RL is the algorithms themselves, not the script-like part of the experiment where things are put together (see the main function in our example). With a framework, in the sense of Kovacs and Egginton (2011), the experiment is not directly accessible to the user programs, since it is handled by some libraries in order to offer graphical interface or analyzing tools. The user code is then called by the framework when required. We advocate that allowing the user to call the rllib functionality at his/her convenience provides an open and extensible access to RL for students, researchers and engineers.

Last, the rllib fits the requirements expressed by Kovacs and Egginton (2011, Section 4.3): support of good scientific research, formulation compliant with the domain, allowing for any kind of agents and any kind of approximators, interoperability of components (the Q function of the example can be used for different algorithms and agents), maximization of run-time speed (use of C++ and templates that inline massively the code), open source, etc. Extensions of rllib can be considered, for example for handling POMDPs, and contributions of users are expected. The use of templates is unfortunately unfamiliar to many programmers, but the effort is worth it, since it brings the code at the level of the mathematical formalism, increasing readability (by a rational use of typedefs) and reducing bugs. Even if the approach is dramatically different from existing frameworks, wrappings with frameworks can be considered in further development.

References


