Acacia-Bonsai: A Modern Implementation of Downset-Based LTL Realizability

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Abstract. We describe our implementation of downset-manipulating algorithms used to solve the realizability problem for linear temporal logic (LTL). These algorithms were introduced by Filiot et al. in the 2010s and implemented in the tools Acacia and Acacia+ in C and Python. We identify degrees of freedom in the original algorithms and provide a complete rewriting of Acacia in C++20 articulated around genericity and leveraging modern techniques for better performances. These techniques include compile-time specialization of the algorithms, the use of SIMD registers to store vectors, and several preprocessing steps, some relying on efficient Binary Decision Diagram (BDD) libraries. We also explore different data structures to store downsets. The resulting tool is competitive against comparable modern tools.

Keywords: LTL synthesis · C++ · downset · antichains · SIMD · BDD

1 Introduction

Nowadays, hardware and software systems are everywhere around us. One way to ensure their correct functioning is to automatically synthesize them from a formal specification. This has two advantages over alternatives such as testing and model checking: the design part of the program-development process can be completely bypassed and the synthesized program is correct by construction.

In this work we are interested in synthesizing reactive systems [15]. These maintain a continuous interaction with their environment. Examples of reactive systems include communication, network, and multimedia protocols as well as operating systems. For the specification, we consider linear temporal logic (LTL) [23]. LTL allows to naturally specify time dependence among events that make up the formal specification of a system. The popularity of LTL as a formal specification language extends to, amongst others, AI [13,6,14], hybrid systems and control [5], software engineering [18], and bio-informatics [1].

The classical doubly-exponential-time synthesis algorithm can be decomposed into three steps: 1. compile the LTL formula into an automaton of exponential size [25], 2. determinize the automaton [25,22] incurring a second exponential blowup, 3. and determine the winner of a two-player zero-sum game played
on the latter automaton \cite{24}. Most alternative approaches focus on avoiding the
determinization step of the algorithm. This has motivated the development of so-
called Safra-less approaches, e.g., \cite{17,9,8,27}. Worth mentioning are the on-the-
fly game construction implemented in the Strix tool \cite{21} and the downset-based
(or “antichain-based”) on-the-fly bounded determinization described in \cite{11}
and implemented in Acacia+ \cite{4}. Both avoid constructing the doubly-exponential
deterministic automaton. Acacia+ was not ranked in recent editions of SYNT-
COMP \cite{16} (see \url{http://www.syntcomp.org/}) since it is no longer maintained
despite remaining one of the main references for new advancements in the field
(see, e.g., \cite{10,29,26,19,2}).

Contribution. We present the Acacia approach to solving the problem at hand
and propose a new implementation that allows for a variety of optimization steps.
For now, we have focused on \textit{(Büchi automata) realizability}, i.e., the decision
problem which takes as input an automaton compiled from the LTL formula
and asks whether a controller satisfying it exists. In our tool, we compile the
input LTL formula into an automaton using Spot \cite{7}. We entirely specialize
our presentation on the technical problem at hand and strive to distillate the
algorithmic essence of the Acacia approach in that context. The main algorithm
is presented in Section 3.4 and the different implementation options are listed in
Section 4. Benchmarks are included in Section 6.

2 Preliminaries

Throughout this abstract, we assume the existence of two alphabets, $I$ and $O$;
although these stand for input and output, the actual definitions of these two
terms is slightly more complex: An \textit{input} (resp. \textit{output}) is a boolean combination
of symbols of $I$ (resp. $O$) and it is \textit{pure} if it is a \textit{conjunction} in which \textit{all} the
symbols in $I$ (resp. $O$) appear; e.g., with $I = \{i_1, i_2\}$, the expressions $\top$ (true),
$\bot$ (false), and $(i_1 \lor i_2)$ are inputs, and $(i_1 \land \neg i_2)$ is a pure input. Similarly, an \textit{IO}
is a boolean combination of symbols of $I \cup O$, and it is \textit{pure} if it is a conjunction
in which all the symbols in $I \cup O$ appear. We use $i,j$ to denote inputs and $x,y$
for IOs. Two IOs $x$ and $y$ are \textit{compatible} if $x \land y \neq \bot$.

A \textit{Büchi automaton} $A$ is a tuple $(Q, q_0, \delta, B)$ with $Q$ a set of states, $q_0$ the
initial state, $\delta$ the transition relation that uses IOs as labels, and $B \subseteq Q$ the
set of Büchi states. The actual semantics of this automaton will not be relevant
to our exposition, we simply note that these automata are usually defined to
recognize infinite sequences of symbols from $I \cup O$. We assume, throughout this
paper, the existence of some automaton $A$.

We will be interested in valuations of the states of $A$ that indicate some sort
of progress towards reaching Büchi states—again, we do not go into details here.
We will simply speak of \textit{vectors over $A$} for elements in $\mathbb{Z}^Q$, mapping states to
integers. We will write $\vec{v}$ for such vectors, and $v_q$ for its value for state $q$. In
practice, these vectors will range into a finite subset of $\mathbb{Z}$, with $-1$ as an implicit
minimum value (meaning that $(-1) - 1$ is still $-1$) and an upper bound provided
by the problem.
For a vector \( \vec{v} \) over \( A \) and an IO \( x \), we define a function that takes one step back in the automaton, decreasing components that have seen Büchi states. Write \( \chi_B(q) \) for the function mapping a state \( q \) to 1 if \( q \in B \), and 0 otherwise. We then define \( \text{bwd}(\vec{v}, x) \) as the vector over \( A \) that maps each state \( p \in Q \) to:

\[
\min_{(p,y,q) \in \delta \text{ compatible with } y} (v_q - \chi_B(q)),
\]

and we generalize this to sets: \( \text{bwd}(S, x) = \{ \text{bwd}(\vec{v}, x) \mid \vec{v} \in S \} \). For a set \( S \) of vectors over \( A \) and a (possibly nonpure) input \( i \), define:

\[
\text{CPre}_i(S) = S \cap \bigcup_{x \text{ pure IO}} \text{bwd}(S, x).
\]

It can be proved that iterating \( \text{CPre} \) with any possible pure input stabilizes to a fixed point that is independent from the order in which the inputs are selected. We define \( \text{CPre}^*(S) \) to be that set.

All the sets that we manipulate will be downsets: we say that a vector \( \vec{u} \) dominates another vector \( \vec{v} \) if for all \( q \in Q \), \( u_q \geq v_q \), and we say that a set is a downset if \( \vec{v} \in S \) and \( \vec{u} \) dominates \( \vec{v} \) implies that \( \vec{v} \in S \). This allows to implement these sets by keeping only dominating elements, which form, as they are pairwise nondominating, an antichain. In practice, it may be interesting to keep more elements than just the dominating ones or even to keep all of the elements to avoid the cost of computing domination.

Finally, we define \( \text{Safe}_k \) as the smallest downset containing the all-\( k \) vector. We are now equipped to define the computational problem we focus on:

**BackwardRealizability**
- **Given:** A Büchi automaton \( A \) and an integer \( k > 0 \),
- **Question:** Is there a \( \vec{v} \in \text{CPre}^*(\text{Safe}_k) \) with \( v_{q_0} \geq 0 \)?

We note, for completeness, that (for sufficiently large values of \( k \)) this problem is equivalent to deciding the realizability problem associated with \( A \): the question has a positive answer iff the output player wins the Gale-Stewart game with payoff set the complement of the language of \( A \).

### 3 Realizability algorithm

The problem admits a natural algorithmic solution: start with the initial set, pick an input \( i \), apply \( \text{CPre}_i \) on the set, and iterate until all inputs induce no change to the set, then check whether this set contains a vector that maps \( q_0 \) to 0. We first introduce some degrees of freedom in this approach, then present a slight twist on that solution that will serve as a canvas for the different optimizations.
3.1 Boolean states

This opportunity for optimization was identified in [3] and implemented in Acacia+, we simply introduce it in a more general setting and succinctly present the original idea when we mention how it can be implemented in Section 4.2. We start with an example. Consider the Büchi automaton:

Recall that we are interested in, after CPre has stabilized, whether the initial state can carry a nonnegative value. In that sense, the crucial information associated with $q_0$ is boolean in nature: is its value positive or $-1$? Even further, this same remark can be applied to $q_1$ since $q_1$ being valued 6 or 7 is not important to the valuation of $q_0$. Hence the set of states may be partitioned into integer-valued states and boolean-valued ones. Naturally, detecting which states can be made boolean comes at a cost and not doing it is a valid option.

3.2 Actions

For each IO $x$, we will have to compute $\text{bwd}(\vec{v}, x)$ oftentimes. This requires to refer to the underlying Büchi automaton and checking for each transition therein whether $x$ is compatible with the condition. It may be preferable to precompute, for each $x$, what are the relevant pairs $(p, q)$ for which $x$ can go from $p$ to $q$. We call the set of such pairs the io-action of $x$ and denote it $\text{io-act}(x)$; in symbols:

$$\text{io-act}(x) = \{(p, q) \mid (\exists (p, y, q) \in \delta)[x \text{ is compatible with } y]\} .$$

Further, as we will be computing $\text{CPre}_i(S)$ for inputs $i$, we abstract in a similar way the information required for this computation. We use the term input-action for the set of io-actions of IOs compatible with $i$ and denote it $\text{i-act}(i)$; in symbols:

$$\text{i-act}(i) = \{\text{io-act}(x) \mid x \text{ is an IO compatible with } i\} .$$

In other words, actions contain exactly the information necessary to compute CPre. Note that from an implementation point of view, we do not require that the actions be precomputed. Indeed, when iterating through pairs $(p, q) \in \text{io-act}(x)$, the underlying implementation can choose to go back to the automaton.

3.3 Sufficient inputs

As we consider the transitions of the Büchi automaton as being labeled by boolean expressions, it becomes more apparent that some pure IOs can be redundant. For instance, consider a Büchi automaton with $I = \{i\}, O = \{o_1, o_2\}$, but the only transitions compatible with $i$ are labeled $(i \land o_1)$ and $(i \land \neg o_1)$. Pure IOs compatible with the first label will be $(i \land o_1 \land o_2)$ and $(i \land o_1 \land \neg o_2)$, but
certainly, these two IOs have the same io-actions, and optimally, we would only consider \((i \land o_1)\). However, we should not consider \((i \land o_2)\), as it is compatible with both transitions, but does not correspond to a pure IO. We will thus allow our main algorithm to select certain inputs and IOs:

**Definition 1.** An IO (resp. input) is valid if there is a pure IO (resp. input) with the same io-action (resp. input-action). A set \(X\) of valid IOs is sufficient if it represents all the possible io-actions of pure IOs: \(\{\text{io-act}(x) \mid x \in X\} = \{\text{io-act}(x) \mid x \text{ is a pure IO}\}\). A sufficient set of inputs is defined similarly with input-actions.

### 3.4 Algorithm

We solve BackwardRealizability by computing \(\text{CPre}^*\) explicitly:

**Algorithm 1:** Main algorithm

**Input:** A Büchi automaton \(A\), an integer \(k > 0\)

**Output:** Whether \((\exists \vec{v} \in \text{CPre}^*(\text{Safe}_k))|v_{q_0} \geq 0\)

1. Possibly remove some useless states in \(A\)
2. Split states of \(A\) into boolean and nonboolean
3. Let \(\text{Downset}\) be a type for downsets using a vector type that possibly has a boolean part
4. Let \(S = \text{Safe}_k\) of type \(\text{Downset}\)
5. Compute a sufficient set \(E\) of inputs
6. Compute the input-actions of \(E\)
7. while true do
   8. Pick an input-action \(a\) of \(E\)
   9. if no action is returned then
      10. return whether a vector in \(S\) maps \(q_0\) to a nonnegative value
11. \(S \leftarrow \text{CPre}_a(S)\)

Our algorithm requires that the “input-action picker” used in line [8] decides whether we have reached a fixed point. As the picker could check whether \(S\) has changed, this is without loss of generality.

The computation of \(\text{CPre}_a\) is the intuitive one, optimizations therein coming from the internal representation of actions. That is, it is implemented by iterating through all io-actions compatible with \(a\), applying \(\text{bwd}\) on \(S\) for each of them, taking the union over all these applications, and finally intersecting the result with \(S\).

### 4 The many options at every line

#### 4.1 Preprocessing of the automaton (line 1)

In this step, one can provide a heuristic that removes certain states that do not contribute to the computation. We provide an optional step that detects surely losing states, as presented in [12].
4.2 Boolean states (line 2)

We provide several implementations of the detection of boolean states, in addition to an option to not detect them. Our implementations are based on the concept of bounded state, as presented in [3]. A state is bounded if it cannot be reached from a Büchi state that lies in a nontrivial strongly connected component. This can be detected in several ways.

4.3 Vectors and downsets (line 3)

The most basic data structure in the main algorithm is that of a vector used to give a value to the states. We provide a handful of different vector classes:

- Standard C++ vector and array types (std::vector, std::array). Note that arrays are of fixed size; our implementation pre-compiles arrays of different sizes (up to 300 by default), and defaults to vectors if more entries are needed.
- Vectors and arrays backed by SIMD registers. This makes use of the type std::experimental::simd and leverages modern CPU optimizations.

Additionally, all these implementations can be glued to an array of booleans (std::bitset) to provide a type that combines boolean and integer values. These types can optionally expose an integer that is compatible with the partial order (here, the sum of all the elements in the vector: if $\vec{u}$ dominates $\vec{v}$, then the sum of the elements in $\vec{u}$ is larger than that of $\vec{v}$). This value can help the downset implementations in sorting the vectors.

Downset types are built on top of a vector type. We provide:

- Implementations using sets or vectors of vectors, either containing only the dominating vectors, or containing explicitly all the vectors;
- An implementation that relies on k-d trees, a space-partitioning data structure for organizing points in a k-dimensional space;
- Implementations that store the vectors in specific bins depending on the information exposed by the vector type.

4.4 Selecting sufficient inputs (line 5)

Recall our discussion on sufficient inputs of Section 3.3. We introduce the notion of terminal IO following the intuition that there is no restriction of the IO that would lead to a more specific action:

Definition 2. An IO $x$ is said to be terminal if for every compatible IO $y$, we have $\text{io-act}(x) \subseteq \text{io-act}(y)$. An input $i$ is said to be terminal if for every compatible input $j$ we have $\text{i-act}(i) \subseteq \text{i-act}(j)$.

Proposition 1. Any pure IO and any input is terminal. Any terminal IO and any terminal input is valid.

3 SIMD: Single Instruction Multiple Data, a set of CPU instructions & registers to compute component-wise operations on fixed-size vectors.
Our approaches to input selection focus on efficiently searching for a sufficient set of terminal IOs and inputs. We present here a simple algorithm for computing a sufficient set of terminal IOs.

**Algorithm 2: Computing a sufficient set of terminal IOs**

**Input:** A Büchi automaton \( \mathcal{A} \)

**Output:** A sufficient set of terminal IOs

\[
P \leftarrow \{ \top \}
\]

for every label \( x \) in the automaton do

for every element \( y \) in \( P \) do

\[\text{if } x \land y \neq \bot \text{ then}\]

Delete \( y \) from \( P \)

Insert \( x \land y \) in \( P \)

\[\text{if } \neg (x \land y) \neq \bot \text{ then}\]

insert \( \neg (x \land y) \) in \( P \)

return \( P \)

At this point, we provide 3 implementations of input selection:

- No precomputation, i.e., return pure inputs/IOs;
- Applying Algorithm 2 twice: for IOs and inputs;
- Use a pure BDD approach to do the previous algorithm; this relies on extra variables to have the loop “for every element in \( P \)” iterate only over elements \( y \) that satisfy \( x \land y \neq \bot \).

### 4.5 Precomputing actions (line 6)

Since computing \( \text{CPre}_i \) for an input \( i \) requires to go through \( \text{i-act}(i) \), possibly going back to the automaton and iterating through all transitions, it may be beneficial to precompute this set. We provide this step as an optional optimization that is intertwined with the computation of a sufficient set of IOs; for instance, rather than iterating through labels in Algorithm 2, one could iterate through all transitions, and store the set of transitions that are compatible with each terminal IO on the fly.

### 4.6 Main loop: Picking input-actions (line 8)

We provide several implementations of the input-action picker:

- Return each input-action in turn, until no change has occurred to \( S \) while going through all possible input-actions;
- Search for an input-action that is certain to change \( S \). This is based on the concept of critical input as presented in [3]. This is reliant on how input-actions are ordered themselves, so we provide multiple options (using a priority queue to prefer inputs that were recently returned, randomize part of the array of input-actions, and randomize the whole array).
5 Checking nonrealizability

As mentioned in the preliminaries, for large values of $k$ the BackwardRealizability problem is equivalent to a non-zero sum game whose payoff set is the complement of the language of the given automaton. More precisely, for small values of $k$, a negative answer for the BackwardRealizability problem does not imply the output player does not win the game. Instead, if one is interested in whether the output player wins, a property known as determinacy [20] can be leveraged to instead ask whether a complementary property holds: does the input player win the game?

We thus need to build an automaton $B$ for which a positive answer to the BackwardRealizability translates to the previous property. To do so, we can consider the negation of the input formula, $\neg \phi$, and inverse the roles of the players, that is, swap the inputs and outputs. However, to make sure the semantics of the game is preserved, we also need to have the input player play first, and the output player react to the input player’s move. To do so, we simply need to have the outputs moved one step forward (in the future, in the LTL sense). This can be done directly on the input formula, by putting an $X$ (neXt) operator on each output. This can however make the formula much more complex.

We propose an alternative to this: Obtain the automaton for $\neg \phi$, then push the outputs one state forward. This means that a transition $(p, \langle i, o \rangle, q)$ is translated to a transition $(p, i, q)$, and the output $o$ should be fired from $q$. In practice, we would need to remember that output, and this would require the construction to consider every state $(q, o)$, augmenting the number of states tremendously. Algorithm 3 for this task, however, tries to minimize the number of states $(q, o)$ necessary by considering nonpure outputs that maximally correspond to a non-pure input compatible with the original transition label.

**Algorithm 3:** Modifying $\mathcal{A}$ so that the outputs are shifted forward

**Input:** A Büchi automaton $\mathcal{A}$ with initial state $q_0$

**Output:** The states $S$ and transitions $\Delta$ of the Büchi automaton $B$

1. $S, V \leftarrow \{(q_0, \top)\}$, $\Delta \leftarrow \{\}$
2. while $V$ is nonempty do
   1. Pop $(p, o)$ from $V$
   2. for every $(p, x, q) \in \delta$ do
      1. Let $y$ be a local output compatible with $x$
      2. Let $i$ be an input s.t. $i \wedge o' \equiv y \wedge o'$
      3. $o'' \leftarrow \exists I, i \wedge y$
      4. Add $(\langle p, o \rangle, o' \wedge i, \langle q, o'' \rangle)$ to $\Delta$
   3. Add $(q, o')$ to $S$ and $V$ and$\top$
5. return $S, \Delta$
6 Benchmarks

6.1 Protocol

For the past few years, the yardstick of performance for synthesis tools is the SYNTCOMP competition [16]. The organizers provide a bank of nearly a thousand LTL formulas, and candidate tools are ran with a time limit of one hour on each of them. The tool that solves the most instances in this timeframe wins the competition.

To benchmark our tool, we selected all the LTL formulas that were accepted in less than 100 seconds by any tool that competed in the 2021 SYNTCOMP competition. These are 879 out of 945 tests. Notably, 864 of these tests were solved in less than 20 seconds by some tool, and among the 66 tests left out, 50 were not solved by any tool. This displays a usual trend of synthesis tools: either they solve an instance fast, or they are unlikely to solve it at all. To better focus on the fine performance differences between the tools, we set a timeout of 15 seconds for all tests.

We compared Acacia-Bonsai against itself using different choices of options, and against Acacia+ [4], Strix [21], and ltlsynt [7]. The benchmarks were completed on a headless Linux computer with the following specifications:

- CPU: Intel® Core™ i7-8700 CPU @ 3.20GHz. This CPU has 6 hyper-threaded cores, meaning that 12 threads can run concurrently. It supports Intel® AVX2, meaning that it has SIMD registers of up to 256 bits.
- Memory: The CPU has 12 MiB of cache, the computer has 16 GiB of DDR4-2666 RAM.

6.2 Results

The options of Acacia-Bonsai. We compared about 30 different configurations of Acacia-Bonsai, in order to single out the best combination of options.

- Preprocessing of the automaton (Section 4.1). This seems to have little impact, although a handful of tests saw an important boost. Overall, the performances were worse with automaton preprocessing, owing to the cost of computing the surely losing states. Overall, we elected to leave the option activated in our best configuration.

- Boolean states (Section 4.2). Using boolean states boosted performances by a marginal amount when SIMD was activated, but had a more important impact when SIMD was deactivated. This follows the intuition that, thanks to bitmasks, boolean states allow for vectorized computing, and they are thus of a lesser impact when native vectorized computing is possible.

- Vectors and downsets (Section 4.3). For the vector implementation to become a bottleneck, specific implementations of downsets have to be selected. Although downsets implemented using k-d trees do not outperform the other implementations with SIMD deactivated, they perform significantly better with SIMD. We show in our main graphic the impact of deactivating SIMD with k-d trees.
- Precomputing a sufficient set of inputs and IO (Section 4.4). This comes with a significant boost in speed (shown in the graph below when comparing all implementations). Among our different implementations to find a sufficient set, Algorithm 2 turned out to offer the best performances.
- Picking input-actions (Section 4.6). The approaches performed equivalently, with a slight edge for the choice of critical inputs without randomizing or priority queue.
- Nonrealizability (Section 5). Computation of the nonrealizability automaton using Algorithm 3, rather than applying $X$ on the outputs of the formula, allowed to solve 14% more instances. In practice, we elected to create two processes for nonrealizability, one for each option, allowing for parallel computation on the two resulting automata.

Acacia-Bonsai and foes. The following graph shows the performance of the tools. Since these tools tend to solve a lot of instances under one second, we elected to present this graphic with a logarithmic y-axis. Thanks to this, the cost of entry of SIMD instructions is also emphasized.

7 Conclusion

We provided six degrees of freedom in the main algorithm for downset-based LTL realizability and implemented multiple options for each of these degrees. In this paper, we presented the main ideas behind these. Experiments show that this careful reimplementation surpasses the performances of the original Acacia+, making Acacia-Bonsai competitive against modern LTL realizability tools. Our implementation can be found at [https://github.com/gaperez64/acacia-bonsai/](https://github.com/gaperez64/acacia-bonsai/).
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