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Implementing Realistic Asynchronous Automata

S. Akshay\textsuperscript{1}, Ionut Dinca\textsuperscript{2}, Blaise Genest\textsuperscript{3}, and Alin Stefanescu\textsuperscript{2}

1 Indian Institute of Technology, Bombay, India
2 University of Pitesti, Romania
3 CNRS, IRISA, Rennes, France

Abstract

Zielonka’s theorem, established 25 years ago, states that any regular language closed under commutation is the language of an \textit{asynchronous automaton} (a tuple of automata, one per process, exchanging information when performing common actions). Since then, constructing asynchronous automata has been simplified and improved [6, 20, 12, 8, 4, 2, 21, 22].

We first survey these constructions and conclude that the synthesized systems are not \textit{realistic} in the following sense: existing constructions are either plagued by deadends, non deterministic guesses, or the acceptance condition or choice of actions are not distributed. We tackle this problem by giving (effectively testable) necessary and sufficient conditions which ensure that deadends can be avoided, acceptance condition and choices of action can be distributed, and determinism can be maintained. Finally, we implement our constructions, giving promising results when compared with the few other existing prototypes synthesizing asynchronous automata.

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1 Introduction

Designing distributed systems is notoriously difficult and prone to bugs. Verification algorithms are very useful to detect and report bugs, but the discovered issues must be solved by the designer. An alternative is to use automatic implementation tools, which directly \textit{synthesize} an implementation that is guaranteed to be correct by construction. As the complexity of automatic implementation is quite high in the general case of \textit{open} distributed systems (distributed games) [9], we focus on closed systems in this paper.

Here, the specification is given as a regular language $L$ over an alphabet $\Sigma$ where every action (i.e., letter in $\Sigma$) is associated with the set of processes managing that action. Such

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure1}
  \caption{Expressivity of different types of asynchronous automata (AA)}
\end{figure}
a specification allows to reason globally about the requirements, instead of having to deal carefully with partial views of each process in a distributed manner (which is one of the error-prone tasks). The problem is then to automatically implement a (truly) distributed control that will globally have the same behavior as the given specification language $L$. Of course, not all languages can be implemented with such a distributed control. For instance, if $ab$ is the only word in the specification language, with $a$ an action local to a process and $b$ local to another process, then it cannot be implemented in a truly distributed manner. Indeed, any distributed implementation will also feature the word $ba$, since a process is unable to know when another process performs an (independent) action.

Zielonka’s theorem, established 25 years ago [23], states that this is sufficient: every language closed by this commutation relation can be implemented in the form of an asynchronous automaton, that is, a network of automata where the control is mostly distributed, and two processes can exchange information whenever they perform a common action. Initially, this was merely an expressiveness result and was believed to be rather impractical due to its prohibitive complexity. During subsequent years, this construction has been simplified and improved in several works [6, 20, 7, 12, 8]. Also, different constructions [4, 2, 21] and heuristics [22] have been proposed to handle the complexity blow-up.

However, none of these constructions gives a general realistic distributed implementation: either the constructions are plagued by deadends [23, 6, 20, 7, 12, 8, 2, 4], non-deterministic guesses [24, 5, 2], or the acceptance condition or choice of actions are not distributed [23, 6, 20, 7, 12, 8]. Further, while the initial state is trivially distributed in Zielonka’s construction (since it is unique, due to determinism), this is not the case in [24, 5]. One cannot always obtain an implementation satisfying all these conditions: we schematically depict in Figure 1 the relations between corresponding subclasses, proved in Proposition 6.

Thus, our main goal is to characterize the class of regular languages that can be implemented by a realistic asynchronous automaton, i.e., one which is deterministic, deadend-free, and has distributed final states and choice of actions. This notion strictly subsumes the class of deadend-free synchronized product of automata [17]. Our central result provides semantical and syntactical characterizations of languages of realistic asynchronous automata, together with algorithms to check these characterizations. Thus, given a global regular specification passing these algorithmic tests, we build a realistic asynchronous automaton which distributedly implements the specification. Finally, we implement our procedure, based on the latest, state of the art variant of Zielonka’s construction [8].

The paper is structured as follows. In section 2, we define (realistic) asynchronous automata, and restate the different implementation theorems. In section 3, we come up with semantical and syntactical characterizations of realistic asynchronous automata. In section 4, we exhibit algorithms to test the characterizations and analyze their complexity. In section 5, we experiment and compare the automatic distributed implementation of different specifications.
2 Realistic Asynchronous Automata

Let $\mathcal{P}$ be a fixed set of processes. A distributed alphabet $(\Sigma, \text{dom})$ is a finite set $\Sigma$ of actions together with the domain function $\text{dom} : \Sigma \to 2^\mathcal{P} \setminus \emptyset$, which associates to each action $a$ the set $\text{dom}(a)$ of processes executing $a$. For any $p \in \mathcal{P}$, we also denote $\Sigma_p = \{ a \in \Sigma \mid p \in \text{dom}(a) \}$.

We say that actions $a$ and $b$ are independent, denoted $(a, b) \in I$, iff $\text{dom}(a) \cap \text{dom}(b) = \emptyset$.

This gives rise to an equivalence relation on words: first, for all words $v, w \in \Sigma^*$ and actions $(a, b) \in I$, we define $vabaw \equiv_1 vbaaw$. Then, the transitive reflexive closure of $\equiv_1$, denoted $\equiv$, is an equivalence relation. The equivalence class containing $v$, denoted $[v]$, is called a (Mazurkiewicz) trace [7]. Given a word $w \in \Sigma^*$ and a process $p \in \mathcal{P}$, the $p$-view of $w$, denoted $\text{view}_p(w)$, is the shortest trace $[v]$ such that: there exists $v'$ with $v \equiv v'$, and each action $a \in \Sigma_p$ occurs as many times in $v$ as in $w$. Finally, for a language $L \subseteq \Sigma^*$, $\text{pref}(L)$ will denote its set of prefixes and $\epsilon$ will denote the empty string.

An asynchronous automaton is a tuple $((S_p)_{p \in \mathcal{P}}, (\Delta_a)_{a \in \Sigma}, I, \text{Fin})$, where for all $p \in \mathcal{P}$, $S_p$ is the set of local states of process $p$, and for all $a \in \Sigma$, $\Delta_a \subseteq \prod_{p \in \text{dom}(a)} S_p \times \prod_{p \in \text{dom}(a)} S_p$ defines the (partial) transition relation. Note that while we define the transition relation on letters for ease of presentation, it is equivalent to a corresponding definition on processes. Any $s = (s_p)_{p \in \mathcal{P}} \in \prod_{p \in \mathcal{P}} S_p$ is called a global state and $\text{Fin} \subseteq (S_p)_{p \in \mathcal{P}}$ denote the set of global initial and final states, respectively.

The semantics of an asynchronous automaton $AA = ((S_p)_{p \in \mathcal{P}}, (\Delta_a)_{a \in \Sigma}, I, \text{Fin})$ is given by the (sequential) automaton $S(AA) = (C, \rightarrow, I, \text{Fin})$ over $\Sigma$, where $C = \prod_{p \in \mathcal{P}} S_p$ is the set of global states, and the global transition relation is given by $\rightarrow: C \to C$ with $(s_p)_{p \in \mathcal{P}} \rightarrow (s'_p)_{p \in \mathcal{P}}$ iff $(s'_p)_{p \in \text{dom}(a)} \in \Delta_a((s_p)_{p \in \text{dom}(a)})$ and $s'_p = s_p$ for all $p \notin \text{dom}(a)$. As usual, we extend $\rightarrow$ to words by fixing for $\epsilon$ the empty word: for all $s, s' \in C$, $s \rightarrow s'$ iff $s' = s$ and $s \xrightarrow{\alpha \sigma} s''$ if there exists $s'' \in C$ with $s \xrightarrow{\alpha} s'$ and $s'' \xrightarrow{\sigma} s'$. In case $\rightarrow$ is deterministic (which is the case for deterministic asynchronous automata), we will denote $\delta_w(s)$ for the unique state $s' \in C$ (if it exists) such that $s \xrightarrow{w} s'$. The language $L(AA)$ accepted by $AA$ is by definition $L(S(AA))$, the language accepted by $S(AA)$.

An automaton $A = (C, \rightarrow, I, \text{Fin})$ is diamond [7] if for all $s, s', t \in C$ and all $(a, b) \in I$, if $s \xrightarrow{a} s' \xrightarrow{b} t$, then there exists $t'$ with $s \xrightarrow{b} t' \xrightarrow{a} t$. For any given asynchronous automaton $AA, S(AA)$ is diamond [7], which implies that $L(AA)$ is closed by commutation: for all $v \in L(AA)$ and $w \equiv v$, we also have $w \in L(AA)$.

An asynchronous automaton, as defined above, cannot always be implemented in a distributed manner, without adding further restrictions. For instance, the set of final states is currently given globally. To obtain purely distributed implementations, we now introduce several restrictions on asynchronous automata.

- **Definition 1** (determinism). An asynchronous automaton $AA = ((S_p)_{p \in \mathcal{P}}, (\Delta_a)_{a \in \Sigma}, I, \text{Fin})$ is deterministic, if $|I| = 1$ and $|\Delta_a(s)| \leq 1$ for all $a \in \Sigma$ and $s \in \prod_{p \in \text{dom}(a)} S_p$.

Non-determinism allows a process to guess what another process is doing concurrently. Note that every asynchronous automaton can be transformed into a deterministic asynchronous automaton, albeit with an unavoidable blow-up in the number of states [14].

- **Definition 2** (deadend-freeness). A global state $s$ is called a deadend, if there does not exist a word $w \in \Sigma^*$ and global state $s' \in \text{Fin}$ with $s \xrightarrow{w} s'$. An asynchronous automaton is deadend-free if no global state reachable from an initial state is a deadend: for all $v \in \Sigma^*$, $s_0 \in I$, and all $s$ with $s_0 \xrightarrow{v} s$, the state $s$ is not a deadend.

Deadend-freeness prevents a process from performing actions that will not be observable in terms of the language. For instance, consider two processes $p, q$ and actions $a, b, c$ such that...
States of process $p$ (resp. $q$) are unshaded (resp. shaded). Dashed lines mark global final states.}

$\text{dom}(a) = p$, $\text{dom}(b) = q$ and $\text{dom}(c) = \text{dom}(d) = \{p, q\}$. Then, the language $L_1 = \{ac, bd\}$ cannot be implemented deterministically and without deadends. Indeed, both $a$ and $b$ are allowed from the initial state (which is unique, if the implementation is deterministic), and thus any realistic implementation would also allow $ab$ (and $ba$), as $\text{dom}(a) \cap \text{dom}(b) = \{p\} \cap \{q\} = \emptyset$. However, an asynchronous automaton with deadends can implement this language as shown in Figure 2(a): the state reached after reading the trace $[ab]$ is a deadend.

**Definition 3** (local acceptance). An asynchronous automaton $((S_p)_{p \in \mathcal{P}}, (\Delta_a)_{a \in \Sigma}, In, Fin)$ is said to be **locally accepting** or have local final states, if $\text{Fin} = \prod_{p \in \mathcal{P}} Fin_p$ for some $\text{Fin}_p \subseteq S_p$ for all $p \in \mathcal{P}$.

Local final states ensure that processes can stop locally, and there is no supervisor which looks at all processes at the same time to choose to stop them. Note that the asynchronous automaton in Figure 2(a) has local final states. Now, the language $L_2 = \{ab, ba, a'b', b'a', a'bc, ba'c, ab'c, b'ac\}$ with $\text{dom}(a) = \text{dom}(a') = p$, $\text{dom}(b) = \text{dom}(b') = q$, and $\text{dom}(c) = \{p, q\}$ cannot be accepted by a deterministic asynchronous automaton having local final states as local states reached on $p$ after $a, a'$ and local states reached on $q$ after $b, b'$ can all be final, depending what the other process did. However, there is a deadend-free deterministic asynchronous automaton with global final states accepting this language, as shown in Figure 2(b). Here, the global final states reached after reading $[ab]$ and $[a'b']$ cannot be expressed as a product of local final states (without also accepting $[ab'], [a'b']$).

**Definition 4** (locally enabled). An asynchronous automaton $((S_p)_{p \in \mathcal{P}}, \Delta, In, Fin)$ is called **locally enabled**, if for all reachable global states $s = (s_p)_{p \in \mathcal{P}}$, $s' = (s'_p)_{p \in \mathcal{P}}$, and $s'' = (s''_p)_{p \in \mathcal{P}}$, if there exist $a \in \Sigma$ and global states $t, t'$ with $s''_p \in \{s_p, s'_p\}$ for all $p \in \text{dom}(a)$ and $s \xrightarrow{a} t$ and $s' \xrightarrow{a} t'$, then there exists a global state $t''$ with $s'' \xrightarrow{a} t''$.

Local enabledness prevents the processes from taking into account the state of other processes to decide whether they should propose an action or not. In terms of distributed control, process based controllers [9] have this property, while action based controllers [11] do not. The asynchronous automata in Figure 2(a,b) are locally enabled. In a distributed implementation, non-local enabledness is not realistic. For instance, consider the language $L_3 = \{abd, bad, a'bc, ba'c, ab'c, b'ac, a'b'd, b'a'd\}$, with $\text{dom}(a) = \text{dom}(a') = p$, $\text{dom}(b) = \text{dom}(b') = q$ and $\text{dom}(c) = \text{dom}(d) = \{p, q\}$. Intuitively, processes $p, q$ should synchronize
with \(d\) if they did both \(a, b\) or \(a', b'\), and with \(c\) if they did \(a, b'\) or \(a', b\). This language cannot be realized by a deadend-free and locally enabled asynchronous automaton. However, the deadend-free and locally accepting asynchronous automaton shown in Figure 2(c) accepts \(L_3\), but it is not locally-enabled.

Ideally, we would like a realistic distributed implementation to satisfy all the properties of determinism, deadend-freeness, local acceptance and local enabledness and not just some of them. Thus, by combining all the above desired properties of a distributed implementation we arrive at our proposal for a realistic asynchronous automaton.

**Definition 5.** An asynchronous automaton \(AA\) is said to be realistic, if \(AA\) is deterministic, deadend-free, has local final states, and is locally enabled.

With this definition, language \(L_3\) above cannot be accepted by a realistic asynchronous automaton (because of local enabledness). Using languages \(L_1, L_2, L_3\), we conclude:

**Proposition 6.** The inclusions schematically represented in Figure 1, between the expressive powers of the above introduced restrictions of asynchronous automata, are strict. Further, the classes of deterministic deadend-free and deterministic locally accepting asynchronous automata have incomparable expressive power.

**Proof.** First, the fact that asynchronous automata and deterministic asynchronous automata have the same expressive power is proved in Theorem 8(1).

Second, \(L_1 = \{ac, bd\}\), with \(\text{dom}(a) = p, \text{dom}(b) = q\) and \(\text{dom}(c) = \text{dom}(d) = \{p, q\}\), is accepted by a deterministic locally accepting asynchronous automaton (see Figure 2) but not by any deterministic deadend-free asynchronous automata. Indeed, by contradiction, if \(L(AA) = L_1\) with \(AA\) deterministic and deadend-free, then denoting by \((s_0', s_0)\) the initial state of \(AA\), we have \(\Delta_a(s_0') = s\) and \(\Delta_b(s_0') = t\) for some local states \(s, t\) of \(p\) and \(q\). Thus \((s, t)\) is a global state reachable by \(ab\). As \(AA\) is deadend-free, there exists \(w\) with \((s, t) \xrightarrow{w} f\) with \(f\) accepting. It means that \(abw \in L_1\), a contradiction.

Third, \(L_2\) is accepted by a deterministic deadend-free asynchronous automaton (see Figure 2) but not by any deterministic locally accepting asynchronous automata. Indeed, by contradiction, if \(L(AA) = L_2\) with \(AA\) deterministic and locally accepting, then denoting by \((s_0', s_0)\) the initial state of \(AA\), we have \(\Delta_a(s_0') = s\), \(\Delta_b(s_0') = s'\), \(\Delta_b(s_0') = t\) and \(\Delta_b(s_0') = t'\). Now, \(ab, ab' \in L_2\) hence \((s, t)\) and \((s', t')\) are final. It means that \(s, s', t, t'\) are local final states as \(AA\) is locally accepting, and thus \((s, t')\) and \((s', t)\) are final. Thus \(ab' \in L_2\), a contradiction.

Last, the expressive power of realistic asynchronous automata is strictly included into the expressive power of deterministic deadend-free and locally accepting asynchronous automata. Indeed, \(L_3\) is accepted by a deterministic deadend-free and locally accepting asynchronous automaton (see Figure 2). Now, assume by contradiction that there exists a deterministic deadend-free locally enabled asynchronous automaton \(AA\) accepting \(L_3\). Denoting by \((s_0', s_0)\) the initial state of \(AA\), we have \(\Delta_a(s_0') = s\), \(\Delta_b(s_0') = s'\), \(\Delta_b(s_0') = t\) and \(\Delta_b(s_0') = t'\). Consider the global states \((s, t); (s', t'); (s, t')\). We have \((s,t) \xrightarrow{d} (s_2, t_2)\) and \((s', t') \xrightarrow{d} (s_2', t_2')\) for some \(s_2, s_2', t_2, t_2'\). Hence there exists a global state \((s_2', t_2')\) such that \((s, t') \xrightarrow{w} (s_2', t_2')\). As \(AA\) is deadend-free, there exists a global final state \(r\) and a word \(w\) such that \((s_2', t_2') \xrightarrow{w} r\). Thus \(abdw \in L_3\), a contradiction. \(\square\)

We remark here that the notion of realistic automata as defined above strictly subsumes the notion of (deadend-free) synchronized product of automata [17]. Such an automaton is given by a tuple of automata \(A = (A_p)_{p \in \mathcal{P}},\) one for each process \(p\) on alphabet \(\Sigma_p = \Sigma \cap \text{dom}^{-1}(p)\), such that \(u \in L(A)\) iff \(\pi_p(u) \in L(A_p)\) for all \(p \in \mathcal{P}\), where \(\pi_p(u)\) is the projection of \(u\) on \(\Sigma_p\), that is the actions not in \(\Sigma_p\) are deleted.
Proposition 7. Let \( A = (A_p)_{p \in \mathcal{P}} \) be a (possibly non-deterministic) deadend-free synchronized product of automata. Then there exists a realistic asynchronous automaton \( B \) with \( L(B) = L(A) \). However, the converse does not hold.

Proof. First, one can determinize \( A \) without changing the language and keeping the deadend-freeness. This follows since each local automaton can be determined keeping the same language, and because of the characterization \( u \in L(A) \) iff \( \pi_p(u) \in L(A_p) \). The resulting automaton can be seen as a deterministic deadend-free asynchronous automaton \( B \). By definition of the synchronized product of automata, \( B \) is also locally accepting and locally enabled, that is, \( B \) is a realistic asynchronous automaton, and we have \( L(B) = L(A) \).

To see that the converse does not hold, consider the following language: \( L_5 = \{acb, a'cb'\} \) with \( \text{dom}(a) = \text{dom}(a') = p, \text{dom}(b) = \text{dom}(b') = q, \text{dom}(c) = (p, q) \). This language is easily realizable by a realistic asynchronous automaton. To see that it cannot be realized by the synchronized product of automata, let us argue by contradiction: if \( L_4 \) was the language of a synchronized product of automata \( A = (A_p)_{p \in \mathcal{P}} \), then we would have \( ac, a'c \in L(A_p) \) and \( cb, cb' \in L(A_p) \), and hence we would have \( acb' \in L(A) \), a contradiction. \( \square \)

2.1 Survey of the different constructions

In the past 25 years, several attempts have been made to construct asynchronous automata from regular (commutation-closed) specifications which preserve some (but not all) of these above mentioned properties. We summarize them below.

Theorem 8. Let \( L \) be a regular language closed by commutation. Then, there exists an asynchronous automaton \( AA \) over \((\Sigma, \text{dom})\) with \( L(AA) = L \) such that either:

1. \( AA \) is deterministic [23, 6, 7, 20, 12, 8], or
2. \( AA \) is deadend-free [24] (see also [5] for a proof for message-passing systems), or
3. \( AA \) has local initial and final states [2].

We provide here the worst case space complexities (the number of local states) to obtain a deterministic or non deterministic asynchronous automaton (Det \( AA \), Non Det \( AA \)), given a deterministic or non deterministic diamond automaton \( A \) over a set of processes \( \mathcal{P} \):

<table>
<thead>
<tr>
<th>complexity</th>
<th>Det ( AA )</th>
<th>Non Det ( AA )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Det ( A )</td>
<td>( A^{O(</td>
<td>\mathcal{P}</td>
</tr>
<tr>
<td>Non Det ( A )</td>
<td>( 2^{O(</td>
<td>\mathcal{P}</td>
</tr>
</tbody>
</table>

The complexities stated to obtain a deterministic asynchronous automaton from [12, 8] are optimal, while optimality is not proven for obtaining a non deterministic asynchronous automaton (using [2] for instance). Note that [2] uses a construction not based on Zielonka’s. Determinizing an asynchronous automaton is possible, but the blow-up is doubly exponential [14]: constructing a deterministic asynchronous automaton directly is preferable. Notice that the complexity is much better in case where the architecture is constrained to be a tree, see [18].

3 Obtaining Realistic Asynchronous Automata

We now turn to the question of characterizing regular languages \( L \) for which there exists a realistic asynchronous automaton \( AA \) such that \( L(AA) = L \). We will give necessary and sufficient semantical conditions on \( L \) to have a realistic distributed implementation \( AA \) accepting \( L \). Further, we will provide syntactical conditions on automata to be equivalent...
to realistic distributed implementations, and prove that a diamond automaton with such conditions is always constructible. Our proofs are constructive, in that they provide realistic asynchronous automata. We also offer characterizations for subsets of realistic properties.

Our main proof can use any of the variants of the Zielonka construction from [23, 6, 7, 20, 12, 8] as a “black box”, without having to reprove them. Moreover, the changes we make to the implementation obtained from the Zielonka construction do not add states.

3.1 A Theoretical Characterization of Realistic AA

Before stating the main theoretical result of the paper, we first define the syntactical and semantical restrictions which will enable realistic asynchronous automata. Recall that we defined the notion of \( \text{view}_p(u) \) in Section 2, which stands for all actions of \( u \) that \( p \) has seen directly or indirectly (through a common action). For instance, let \( \text{dom}(a) = p, \text{dom}(b) = q \) and \( \text{dom}(c) = \{p, q\} \). Then \( \text{view}_p(abcb) \equiv abc \) since \( c \) is “seen” by \( p \) \( (p \in \text{dom}(c)) \) and \( b \) is “before” \( c, b \) and \( c \) are not independent as \( \text{dom}(b) \cap \text{dom}(c) = \{q\} \neq \emptyset \).

\begin{align*}
\textbf{Definition 9} \ (\text{Semantical conditions}). & \text{ For language } L, \text{ we define the following conditions:} \\
\text{(LC1) forward diamond:} & \text{ Whenever } w \in \Sigma^*, (a, b) \in I \text{ and } wa, wb \in \text{pref}(L), \text{ we have } wab \in \text{pref}(L). \\
\text{(LC2) causally closed:} & \text{ Whenever } w \in \Sigma^*, \text{ if for all } p \in P \text{ there exists } v_p \in L \text{ with } \text{view}_p(v_p) = \text{view}_p(w) \text{, then } w \in L. \\
\text{(LC3) locally closed:} & \text{ Whenever } w \in \text{pref}(L), \text{ if for all actions } c \text{ and all } p \in \text{dom}(c), \text{ there exists } v_pc \in \text{pref}(L) \text{ with } \text{view}_p(v_p) = \text{view}_p(w), \text{ then } wc \in \text{pref}(L). \\
\end{align*}

The first two language conditions (LC1,LC2) have been defined before (in the different setting of Message Sequence Charts for (LC2) [1]), and their names are standard in the Mazurkiewicz trace community. However, they have only been considered separately; and the third notion (LC3) is new.

\begin{align*}
\textbf{Definition 10} \ (\text{Syntactical conditions}). & \text{ For a sequential diamond deterministic automaton } A = (C, \rightarrow, I_n, F_i), \text{ we define the following conditions:} \\
\text{(AC1) forward diamond:} & \text{ Whenever } s, s', t' \in C, (a, b) \in I \text{ with } s \xrightarrow{a} s' \text{ and } s \xrightarrow{b} t', \text{ there exists a state } t \text{ with } s' \xrightarrow{b} t \text{ and } t' \xrightarrow{a} t. \\
\text{(AC2) Whenever } s \in C, \text{ if for all } p \in \text{dom}(a) \text{ there exist } r^p, t^p \in C \text{ and words } w^p, (w')^p \in (\Sigma \setminus \Sigma_p)^*, \text{ such that } r^p \xrightarrow{w^p} s \text{ and } r^p \xrightarrow{(w')^p} t^p \text{ and } t^p \in F_i, \text{ then } s \in F_i. \\
\text{(AC3) Whenever } s \in C \text{ and } a \in \Sigma, \text{ if for all } p \in \text{dom}(a) \text{ there exist } r^p, t^p, x^p \in C \text{ and words } w^p, (w')^p \in (\Sigma \setminus \Sigma_p)^*, \text{ such that } r^p \xrightarrow{w^p} s \text{ and } r^p \xrightarrow{(w')^p} t^p \xrightarrow{a} x^p, \text{ then there exists } t' \in C \text{ with } s \xrightarrow{a} t'. \\
\end{align*}

The first automaton condition (AC1) has been defined earlier, while the two others are new. Our main theorem below shows that these local syntactical conditions have a global semantical implication.

To illustrate (LC3) and (AC3), consider the language \( L_3 \) in Section 2 (Figure 2(c)). We observe that \( L_3 \) does not meet (LC3) as \( w = ab \in \text{pref}(L_3), \text{ dom}(c) = \{p, q\}, ab'c \in \text{pref}(L_3) \) with \( \text{view}_p(ab') = [a] = \text{view}_p(w) \) and \( ab'c \in \text{pref}(L_3) \) with \( \text{view}_q(a'b) = [b] = \text{view}_q(w) \) but \( wc \notin \text{pref}(L_3) \). Further, if \( A_3 \) is a deterministic automaton with \( L(A_3) = L_3 \), denoting by \( s_w \) the state reached after \( w \), we consider state \( s_{ab} \) and action \( c \). Then, letting \( r^p = s_a, w^p = b', t^p = s_{ab} \) and \( r^q = s_b, w^q = a', t^q = s_{ab} \) it follows that \( A_3 \) does not satisfy (AC3).

\begin{align*}
\textbf{Theorem 11.} & \text{ Let } L \text{ be a regular language. Then, the following are equivalent:} \\
\end{align*}
Theorem 11 is shown by proving (doable in polynomial time (see section 4).\[A\] states). For complexity issues, we expect that \(\text{A}\) does not add any state or transition to \(8\) (though it may result in the removal of some synchronous automaton by applying the algorithm from \(8\). Then, a realistic asynchronous deterministic automaton \(\text{A}\) satisfying (AC1,AC2,AC3). Indeed, checking that \(\text{A}\) fulfills (AC1,AC2,AC3) is doable in polynomial time (see section 4).

3.2 Proof of Theorem 11

Theorem 11 is shown by proving \((1 \implies 2)\), then \((2 \implies 3)\), and last \((3 \implies 1)\).

3.3 From (AC1,AC2,AC3) to (LC1,LC2,LC3): Theorem 11(1 \implies 2)

We start the proof of Theorem 11 by proving that for any reachable and co-reachable diamond deterministic automaton \(\text{A}\) satisfying (AC1,AC2,AC3), then \(\mathcal{L}(\text{A})\) is closed by commutation and satisfies (LC1,LC2,LC3).

Firstly, as \(L\) is diamond, we get that \(\mathcal{L}(\text{A})\) is closed by commutation. Then:

\(\text{(LC1): Let } w \in \Sigma^*, (a,b) \in I \text{ such that } wa, wb \in \text{pref}(\mathcal{L}(\text{A})). \text{ By (AC1) we have that } In \xrightarrow{wab} \text{ is defined, and because every state of } A \text{ is co-reachable, we have that } wab \in \text{pref}(L).\)

\(\text{(LC2): Let } w \in \Sigma^* \text{ such that for all } p \in \mathcal{P}, \text{ there exists } v_p \in \mathcal{L}(\text{A}) \text{ with } \text{view}_p(v_p) = \text{view}_p(w). \text{ As } A \text{ satisfies (AC1), } In \xrightarrow{w} s \text{ is defined. We let } v_p = \text{view}_p(v_p)v'_p \text{ and } w = \text{view}_p(w)v_p \text{ for all } p \in \mathcal{P}. \text{ We define } In \xrightarrow{\text{view}_p(v_p)=\text{view}_p(w)} r^p \text{ and } r^p \xrightarrow{v'_p} t^p. \text{ As } v_p \in L \text{ and } A \text{ deterministic, we have that } t^p \text{ is final. Also, we have } r^p \xrightarrow{w_p} s. \text{ By (AC2), we thus have } s \in F, \text{ that is, } w \in \mathcal{L}(\text{A}). \text{ (Note that, here and below, for a global state } s \text{ we use } s^p \text{ to denote the } p\text{-local component and hence we use } s^{\text{view}_p} \text{ to denote the global state } s \text{ indexed by process } p. \text{ However for a word } v, v_p \text{ always denotes indexing by process } p \text{ and hence we do not need to change this notation.)}\)

\(\text{(LC3): Let } w \in \text{pref}(L) \text{ and } a \in \Sigma \text{ such that for all } p \in \text{dom}(a), \text{ there exists } v_p,a \in \text{pref}(\mathcal{L}(\text{A})) \text{ with } \text{view}_p(v_p) = \text{view}_p(w). \text{ We define } s \text{ such that } In \xrightarrow{w} s. \text{ We let } v_p = \text{view}_p(v_p)v'_p \text{ and } w = \text{view}_p(w)v_p \text{ for all } p \in \mathcal{P}. \text{ We define } In \xrightarrow{\text{view}_p(v_p)=\text{view}_p(w)} r^p \text{ and } r^p \xrightarrow{v'_p} t^p \xrightarrow{a} x^p. \text{ We have } r^p \xrightarrow{w_p} s. \text{ By (AC3) and as the automaton is co-reachable, we thus have } wa \in \text{pref}(\mathcal{L}(\text{A})).\)

3.4 From (LC1,LC2,LC3) to realistic AA: Theorem 11 (2 \implies 3)

Our basic strategy to construct a realistic AA is to use Theorem 8 (part 1.) to construct a deterministic AA from a given language \(L\) and then refine this AA to obtain a realistic AA which accepts the same language. For this, we will use as our template the recent construction from [8], and hence we begin by stating the relevant result and a definition that we need from this paper.
We can construct a deterministic locally rejecting asynchronous automaton \( AA \) such that \( \mathcal{L}(AA) = \mathcal{L}(A) \). Of course, \( AA \) may still have deadends (or global final states or not be locally enabled). Henceforth, for any static process \( s \xrightarrow{w} t \) with \( t = (t_p)_{p \in P} \), we will denote the (local) state \( t_p \) by \( \delta^p_w(s) \). Notice that as the asynchronous automaton is deterministic, \( \delta^p_w(s) \) is unique (if it exists) for each \( p, w, s \).

First, we show that deadends can be avoided by using the locally rejecting property of \( AA \). We remove all states of \( R_p \) from \( AA = ((S_p)_{p \in P}, (\Delta_a)_{a \in \Sigma}, \{s_0\}, \text{Fin}) \). That is, we define the asynchronous automaton \( AA' = ((S'_p)_{p \in P}, (\Delta'_a)_{a \in \Sigma}, \{s_0\}, \text{Fin}') \) with \( S'_p = S_p \setminus R_p \) for all \( p \in P \), and \( \Delta'_a = \Delta_a \cap \prod_{p \in \text{dom}(a)} S'_p \) for all \( a \in \Sigma \), where \( R = \{(s_p)_{p \in P} \mid \exists q, s_q \in R_q\} \). This means that for some prefix \( w s \), for some process \( p \), \( \delta^p_w(s) = s_q \) (but \( \delta^p_w(s) \in S'_p \)). By definition of \( R_q \), \( \text{view}_q(w) \notin \text{pref}(\mathcal{L}(AA)) \). This is a contradiction with \( \text{view}_q(w) \) is a prefix of \( w \in \mathcal{L}(AA) \).

Thus, we have \( \mathcal{L}(AA) = \mathcal{L}(AA) = L \). To show that \( AA' \) has no deadend. Let \( s = (s_p)_{p \in P} \) be any global state reachable from the initial state \( s_0 \); that is, there exists \( w \) such that for all \( p \), \( \delta^p_w(s) = s_p \). In particular, \( \delta^p_w(s_0) \) is defined for all \( p \). It follows by definition of rejecting states, that \( \text{view}_p(w) \in \text{pref}(\mathcal{L}(AA)) \), for all process \( p \). Now we can prove that \( w \in \text{pref}(\mathcal{L}(AA)) \) using (LC1). Let us first sketch the case when \( |P| = 2 \), denoting \( P = \{p, q\} \). We have \( [w] = [uaxbb'y] \) with \( [uax] = \text{view}_p(w) \in \text{pref}(\mathcal{L}(AA)), [ubbl'y] = \text{view}_q(w) \in \text{pref}(\mathcal{L}(AA)) \) and the domain of any action of \( ax \) and the domain of any action of \( bb'y \) is disjoint. Now, \( uu \) and \( ub \) are in \( \text{pref}(\mathcal{L}(AA)) \), and \( (a, b) \in I \). So by (LC1), we get \( ubu \in \text{pref}(\mathcal{L}(AA)) \). But we also have \( ubb' \in \text{pref}(\mathcal{L}(AA)) \) with \( (a, b') \in I \), hence by (LC1) we get \( ubbl'a \in \text{pref}(\mathcal{L}(AA)) \). Now, a first induction on the length of \( bb'y \) gives \( ubb'yax \in \text{pref}(\mathcal{L}(AA)) \). And a second induction on the length of \( ax \) gives \( ubb'yax \in \text{pref}(\mathcal{L}(AA)) \), that is \( w \in \text{pref}(\mathcal{L}(AA)) \) (as \( \text{pref}(\mathcal{L}(AA)) \) is closed by commutation). This completes the proof for the case of \( |P| = 2 \). And the result follows by a third induction on the number of processes \( |P| \).
Hence we have shown that for any reachable global state \( s \), there exists \( w \in \text{pref}(\mathcal{L}(AA)) \) with \( s = \delta^t_w(s_0) \). Thus there exists \( s \) such that \( wv \in \mathcal{L}(AA) = \mathcal{L}(AA') \), and \( \delta^t_w(s) \) is final as \( AA' \) is deterministic. That is, no reachable global state \( s \) is a deadend. \( \square \)

Now, \( AA' \) may still not be realistic due to final states that are global. To obtain local final states, we define \( \text{Fin}_p = \{ \delta^t_w(s_0) \in S_p \mid w \in L \} \) for all \( p \in \mathcal{P} \) and let \( \text{Fin}' = \prod_{p \in \mathcal{P}} \text{Fin}_p \). Thus, we obtain a new asynchronous automaton \( AA'' = ( (S'_p)_{p \in \mathcal{P}}, (\delta^t_w)_{w \in \Sigma} \cup \{s_0\}, \text{Fin}' \) \), differing from \( AA' \) only in its final states.

\[ \textbf{Lemma 15.} AA'' \text{ is a realistic asynchronous automaton such that } \mathcal{L}(AA'') = \mathcal{L}(AA') = L. \]

\[ \textbf{Proof.} \] By definition, \( AA'' \) is locally accepting, and it is deterministic since \( AA' \) and \( AA \) were deterministic. Also as \( \text{Fin}' \subseteq \text{Fin}'' \), setting the final states to be \( \text{Fin}'' \) does not add a deadend. Next, we show that \( \mathcal{L}(AA'') = \mathcal{L}(AA') = L \). Take a word \( w \in \mathcal{L}(AA'') \). Hence \( \delta^t_w(s_0) \in \text{Fin}_p \) for all \( p \). By definition of \( \text{Fin}_p \), for all \( p \) there exists \( v_p \in \mathcal{L}(AA') = L \) with \( \delta^t_w(s_0) = \delta^t_v(s_0) \). We want to use (LC2) to conclude, but so far, there is no reason that \( \text{view}_p(v_p) = \text{view}_p(w) \) for any \( p \). We will thus build \( v_p' \in L \) such that \( \text{view}_p(v_p') = \text{view}_p(w) \) for every \( p \). Let \( p \in \mathcal{P} \). It suffices to decompose \( [v_p'] = [v_p][y_p] \). We then set \( v_p' = \text{view}_p(w)y_p \) and so \( \text{view}_p(v_p') = \text{view}_p(w) \) for all \( p \). To obtain that \( v_p' \in L \), we use a property of the Zielonka’s construction from a deterministic automaton \( A \): for all words \( w, w' \) such that \( \delta^t_w(s_0) = \delta^t_{w'}(s_0) \), the state of \( A \) reached from the initial state after reading \( \text{view}_p(w) \) is the same as the state reached after reading \( \text{view}_p(w') \) (in other words, the \( p \)-view maintains the information about the state of \( A \) reached by the \( p \)-view of the executed trace). Now, let \( s \) be the state of the minimal deterministic automaton \( A \) for \( L \), reached after reading \( \text{view}_p(v_p') = \text{view}_p(w) \). This is also the state reached after reading \( \text{view}_p(v_p) \) because \( \delta^t_w(s_0) = \delta^t_v(s_0) \) and by the property above. Reading \( y_p \) from \( s \) thus leads to a final state of \( A \), as \( \text{view}_p(v_p)y_p \in L \) and the automaton is deterministic. Thus \( v_p' = \text{view}_p(w)y_p \in L \) too. Applying (LC2), we get \( w \in L = \mathcal{L}(AA') \), and thus \( L = \mathcal{L}(AA') = \mathcal{L}(AA'') \).

It remains to prove that \( AA'' \) is locally enabled: Let \( w^1, w^2, w^3 \) be words with \((s^1_p)_{p \in \mathcal{P}} \) the state reached on \( w^i \) in \( AA'' \) (the state is unique by determinism of \( AA'' \)). Let \( a \) be an action such that \( s^1_p \in \{s^1_p, s^2_p\} \) for all \( p \in \text{dom}(a) \). Assume that \( (s^1_p)_{p \in \mathcal{P}} \prec (t^1_p)_{p \in \mathcal{P}} \) and that \( (s^2_p)_{p \in \mathcal{P}} \prec (t^2_p)_{p \in \mathcal{P}} \) for some \( (t^1_p)_{p \in \mathcal{P}} \) and \( (t^2_p)_{p \in \mathcal{P}} \). As \( AA' \) is dead-end-free, it means that \( w^1a \) and \( w^2a \) are in \( \text{pref}(L) \). We want to show that \( w^3a \in \text{pref}(L) \), which will imply that there exists \( (t^3_p)_{p \in \mathcal{P}} \) and \( (s^3_p)_{p \in \mathcal{P}} \), such that \( (s^3_p)_{p \in \mathcal{P}} \prec (t^3_p)_{p \in \mathcal{P}} \), that is local enabledness of \( AA'' \).

We now use, as above, the property that if \( w, w' \) reach in \( AA \) the same local state \( s_p \) on process \( p \), then \( \text{pref}_p(w), \text{pref}_p(w') \) reach the same state \( s \) in \( A \). We decompose \( \text{dom}(a) \) into two sets: \( P_1, P_2 \) such that \( p \in P_1 \) iff \( s^3_p = s^1_p \). We have that for all \( p \in P_1 \), both \( \text{pref}_p(w^3) \) and \( \text{pref}_p(w^1) \) reach \( s^1_p \) on process \( p \). Hence \( \text{pref}_p(w^3) \) and \( \text{pref}_p(w^1) \) reach in \( A \) the same state \( s^1 \). Writing \( w^1 = \text{pref}_p(w^1)w^p \), we have that for \( w^p = \text{pref}_p(w^3)v^p \), \( w^pa \in \text{pref}(L) \), with \( \text{view}_p(w^p) = \text{pref}_p(w^3) \). The same reasoning for \( p \in P_2 \) gives the existence of some \( w^p \) with \( \text{view}_p(w^p) = \text{view}_p(w^3) \) and \( w^pa \in \text{pref}(L) \). It suffices to apply the definition of \( (LC3) \) to deduce that \( w^3a \in \text{pref}(L) \), which implies that \( AA'' \) is locally enabled. \( \square \)

Notice that \( \text{Fin}_p \) can be computed in time \( O(|A|) \). Indeed, we reuse the property that a local \( p \) state \( \delta^t_w(s_0) \) keeps the state \( s \) of \( A \) reached from the initial state after reading \( \text{view}_p(w) \). To know whether there exists \( w' \in L \) such that \( \delta^t_w(s_0) = \delta^t_{w'}(s_0) \), it suffices to perform one graph search (e.g. DFS) using edges of \( A \) except the ones using letters in \( \Sigma_p \), and see whether a final state of \( A \) is reachable from \( s \) by this search. This takes time \( O(|A|) \).
3.5 From realistic AA to (AC1,AC2,AC3): Theorem 11 (3 \implies 1)

Given a realistic asynchronous automaton $AA = ((S_p)_{p \in P}, \Delta, In, Fin)$, we consider its global (sequential) automaton $S(AA) = (C, \rightarrow, In, Fin)$. We can then prove that (the reachable part of) $S(AA)$ satisfies (AC1, AC2, AC3). As $AA$ is deadend-free, every reachable state $s$ of $S(AA)$ is also co-reachable, that is, there exists $w$ such that $s \xrightarrow{w} s'$ with $s' \in Fin$. First, by construction, as $AA$ is deterministic, $S(AA)$ is deterministic. Further, $S(AA)$ is diamond for any $AA$ as mentioned earlier. Then:

\begin{enumerate}
\item [(AC1):] Let $s, s', t' \in C$ and $(a, b) \in I$ with $s \xrightarrow{a} s'$ and $s \xrightarrow{b} t'$, and $s$ is reachable. That is, there exists $In \xrightarrow{w} s$. We have $In \xrightarrow{wab}$ is defined: indeed, $In \xrightarrow{wab} s' = (s'_p)_{p \in P}$. Now, notice that for all $p \notin \text{dom}(a)$, $s'_p = s_p$. Also, $(s'_p)_{p \in P} \xrightarrow{b} (t_p)_{p \in P}$, with $t_p = s'_p$ for all $p \notin \text{dom}(b)$, and $t_p = t'_p$ for all $p \in \text{dom}(b)$, as dom$(a) \cap$ dom$(b) = \emptyset$. Hence (AC1) is satisfied by $S(AA)$.

\item [(AC2):] Assume that $s \in C$ and that for each $p \in P$, there exist tuples of states and words $(r^p, t^p, w^p, (w^p)'\in P$ such that $r^p \in C$, $t^p \in Fin$ and $w^p, (w^p)' \in (\Sigma \setminus \Sigma_p)^*$ and $r^p \xrightarrow{w^p} s$ and $r^p \xrightarrow{(w^p)'} t^p$. Because $w^p, (w^p)' \in (\Sigma \setminus \Sigma_p)^*$, and by definition of $S(AA)$, we have that $s$ and $t^p$ have the same $p$ state, say $s_p$. Now, $t^p$ is final and $AA$ has local final states, so it means that $s_p$ is final. As this is true for all $p \in P$, it means that $s$ itself is final, since it is a product of all local final states, i.e., $s \in Fin$.

\item [(AC3):] Assume that $s \in C$ and for all $a \in \Sigma$, for all $p \in \text{dom}(a)$ there are tuples $(r^p, t^p, x^p, w^p, (w^p)'\in P_{\text{dom}(a)}$ such that $r^p, t^p, x^p \in C$ and $w^p, (w^p)' \in (\Sigma \setminus \Sigma_p)^*$, $r^p \xrightarrow{w^p} s$, $r^p \xrightarrow{(w^p)'} t^p \xrightarrow{a} x^p$. Again, by definition of $S(AA)$, $s$ and $t^p$ have the same local $p$-state $s_p$. Hence, for every $p \in \text{dom}(a)$, $s_p$ enables $a$ (i.e., $a$ can be fired from $s_p$), and because $AA$ is locally enabled, there exists $s'$ with $s \xrightarrow{a} s'$, which proves (AC3).
\end{enumerate}

3.6 Corollaries

In many (but not all) cases, there is an automaton for $L$ satisfying (ACi) as soon as $L$ is (LCi), for $i = 1, 2, 3$. We first consider the cases where all states are final (see [22]), in which case (LC2) and (AC2) are not useful: The first corollary follows directly by removing (LC2) and (AC2) from Theorem 11, and hence we just state it in full below.

\begin{itemize}
\item [\textbf{Corollary 16.}] Let $L$ be a regular language. Then, the following are equivalent:
\begin{enumerate}
\item There exists a (sequential, finite) deterministic diamond automaton $A = (C, \rightarrow, In, Fin)$ such that every state is reachable from $In$ and every state can reach $Fin$, with $L(A) = L$, and satisfying (AC1) and (AC3).
\item $L$ satisfies (LC1) and (LC3) and is closed under commutation.
\item There exists a deterministic, deadend-free, locally enabled asynchronous automaton $AA$ with $L(AA) = L$, and $AA$ has at most as many states as the asynchronous automaton obtained by applying [8] to the minimal deterministic (sequential) automaton accepting $L$.
\end{enumerate}
\end{itemize}

The following results are useful in section 4 to test if a given asynchronous automaton is realistic, that is, for testing if each of the conditions (LC1),(LC2),(LC3) hold. The following corollary does not follow immediately from what we proved earlier, since it states that we can choose $A$ to be the minimal deterministic automaton. Hence, we state this result in full and also provide an explicit proof.
Corollary 17. Let $L$ be a regular language. Then, the following are equivalent:

1. The minimal (sequential, finite) deterministic diamond automaton $A = (C, \to, In, Fin)$ of $L$ satisfies (AC1).
2. $L$ satisfies (LC1) and is closed under commutation.
3. There exists a deterministic, deadend-free asynchronous automaton $AA$ with $\mathcal{L}(AA) = L$, and $AA$ has at most as many states as the asynchronous automaton obtained by applying [8] to the minimal deterministic (sequential) automaton accepting $L$.

Proof. \cite{Corollary 17} (1) \iff (2) \iff (3) follows from the proof of Theorem 11. We finish the proof by proving (2) \implies (1), that is, for $L$ a regular language closed by commutation satisfying (LC1) and $A$ be the minimal deterministic automaton with $\mathcal{L}(A) = L$, we have that $A$ satisfies (AC1).

Let $s, s', t'$ be three states such that $s \xrightarrow{a} s'$ and $s \xrightarrow{b} t'$ with $(a, b) \in I$. Further let $v$ be any word such that $s_0 \xrightarrow{v} s$ (for initial state $s_0$) and $w, w'$ words such that $s' \xrightarrow{w} r$ and $t' \xrightarrow{w'} r'$ with $r, r' \in F$. All three words exist by minimality of $A$. Then $vaw, vbaw' \in \mathcal{L}(A)$, and so, by (LC1), $vab \in \text{pref}(\mathcal{L}(A))$. That is, there exists a word $u$ with $vabu \in \mathcal{L}(A)$. Now since $A$ is deterministic, we have the existence of $t$ such that $s' \xrightarrow{b} t$. Further, as $\mathcal{L}(A)$ is closed by commutation, we also have $vbau \in \mathcal{L}(A)$, and thus there exists a state $\overline{t}$ with $t' \xrightarrow{w} \overline{t}$. But now, by the minimality of $A$, it follows that $\overline{t} = t$. To see this, note that for all words $u$ such that $vabu \in \mathcal{L}(A)$, we also have $vbau \in \mathcal{L}(A)$. This implies that $t$ and $\overline{t}$ are “equivalent” with respect to the language accepted, and hence in the (unique) minimal automaton $A$, we have $\overline{t} = t$.

In the proof of subsection 3.3, both (AC1) and (AC2) are used to prove (LC2). However, if deadends are allowed, one can alternatively use only (AC2) to prove (LC2) if the deterministic (sequential) automaton $A = (C, \to, In, Fin)$ is complete. We state and prove this result below.

Corollary 18. Let $L$ be a regular language. Then, the following are equivalent:

1. There exists a deterministic diamond complete automaton $A = (C, \to, In, Fin)$ with $\mathcal{L}(A) = L$ satisfying (AC2).
2. $L$ satisfies (LC2) and is closed under commutation.
3. There exists a deterministic (locally enabled) asynchronous automaton $AA$ with local final states and $\mathcal{L}(AA) = L$. Also, if $|S|$ is the number of states of the $AA$ obtained by applying [8] to the minimal deterministic (sequential) automaton accepting $L$, then $AA$ has at most $|S| - |P|$ states.

Proof. (2) \implies (3) \implies (1) follows from the proof of Theorem 11. We finish the proof by proving (1) \implies (2), that is, for any complete diamond deterministic automaton $A$ satisfying (AC2), then $\mathcal{L}(A)$ is closed by commutation and satisfies (LC2).

Firstly, as $L$ is diamond, we get that $\mathcal{L}(A)$ is closed by commutation. Then: Let $w \in \Sigma^*$ such that for all $p \in P$, there exists $v_p \in \mathcal{L}(A)$ with $\text{view}_p(v_p) = \text{view}_p(w)$. As $A$ is complete, $In \xrightarrow{w} s$ is defined. We let $v_p = \text{view}_p(v_p) v_p'$ and $w = \text{view}_p(w) w_p$ for all $p \in P$. We define $In \xrightarrow{\text{view}_p(v_p) = \text{view}_p(w)} r^p$ and $r^p \xrightarrow{w} t^p$. As $v_p \in L$ and $A$ deterministic, we have that $t^p$ is final. Also, we have $r^p \xrightarrow{w} s$. By (AC2), we thus have $s \in F$, that is, $w \in \mathcal{L}(A)$. This ends the proof.

Notice that the above corollary uses the fact that if deadends are allowed, then one can always ensure that an asynchronous automaton is locally enabled, by adding a state on each
process which is a deadend. This fact also means that \( L \) satisfying (LC3) alone is not useful in terms of asynchronous automata.

Finally, if we keep (LC1) and (LC2), we can again use the proofs of the previous section to immediately conclude the following easy yet interesting corollary (when considering action based controllers [11]):

**Corollary 19.** Let \( L \) be a regular language. Then, the following are equivalent:

1. There exists a (sequential, finite) deterministic diamond automaton \( A = (C, \rightarrow, \text{In}, \text{Fin}) \) such that every state is reachable from \( \text{In} \) and every state can reach \( \text{Fin} \), with \( \mathcal{L}(A) = L \), and satisfying (AC1) and (AC2).
2. \( L \) satisfies (LC1) and (LC2) and is closed under commutation.
3. There exists a deterministic, deadend-free asynchronous automaton \( AA \) with local final states and \( \mathcal{L}(AA) = L \), and \( AA \) has at most as many states as the asynchronous automaton obtained by applying [8] to the minimal deterministic (sequential) automaton accepting \( L \).

## 4 Testing for Realistic Asynchronous Automata

We now explain how to check each property (LCi) and (ACi) for all \( i = 1, 2, 3 \).

**Testing automata restrictions (ACi):** Let \( A \) be an automaton, possibly non deterministic. To test (AC1), for each state \( s \) we need to check if it has a pair of outgoing transitions on actions that are independent, and if so, test for the existence of a common state that can be reached, giving a complexity quadratic in the number of states and transitions of \( A \).

To test (AC2), we perform one graph search (e.g. DFS) from each state \( p \in \mathcal{P} \) and for each process \( p \in \mathcal{P} \) to compute the set \( R_p^* \) of states \( r \) with \( r \xrightarrow{w_p} s \) for some \( w_p' \in (\Sigma \setminus \Sigma_p)^* \). This is a simple graph search in linear time, done on the graph with reverse edge and where edges using letters of \( \Sigma_p \) have been deleted. Computing \( R_p^* \) thus takes time linear in the size of the graph. We then perform another graph search from \( R_p^* \) to compute the set \( T_p^* \) of final states \( s \) such that \( r \xrightarrow{w_p} s \), for some \( r \in R_p^* \) and \( w_p \in (\Sigma \setminus \Sigma_p)^* \). Now \( A \) does not satisfy (AC2) iff \( \exists s, \forall p, T_p^* = \emptyset \). Hence, these two graphs search are applied \( |\mathcal{P}| \) times (one for each process) and \( |A| \) times (one for each state \( s \)). Overall, it takes time \( O(|\mathcal{P}| \cdot |A|^2) \). The test of (AC3) is similar, with the same complexity.

**Testing language restrictions (LCi):** We now describe how to test language restrictions. We assume that the language \( L \) to be tested is given as an automaton (possibly non deterministic). First, using Corollary 17, one has a simple way to test for (LC1): compute the minimal deterministic automaton \( A \) with \( \mathcal{L}(A) = L \), and test (AC1) using the polynomial procedure given above at the beginning of the section. This gives a PSPACE algorithm.

The complexity is polynomial if the starting automaton is deterministic.

In order to test for (LC2), we use Corollary 18. Indeed, we build the asynchronous automaton \( AA \) from \( A \) as if \( \mathcal{L}(A) \) satisfies (LC2). This can only add executions to the language, as final states are possibly added. Then we test whether \( \mathcal{L}(AA) \subseteq \mathcal{L}(A) \). If the inclusion holds, then \( A \) satisfies (LC2), else \( A \) does not satisfy (LC2). This gives a PSPACE algorithm. If \( \mathcal{P} \) is not part of the input and \( A \) is deterministic, then it is polynomial time. Notice that one cannot resort, as in the case of (LC1), to using the minimal automaton associated to \( L \). This minimal automaton may not necessarily satisfy (AC2), even if \( L \) satisfies (LC2). For instance, consider the language \( L_4 = \{ e, a_1, b_1, a_1b_1, b_1a_1 \} \cup \{ a_ibjc, bjadi \mid i, j \in \{1, 2\} \} \) with \( \text{dom}(a_i) = p, \text{dom}(b_i) = q \) for all \( i, j \in \{1, 2\} \) and \( \text{dom}(c) = \{p, q\} \). There
is a state \( t \) in the minimal automaton with \( s_0 \xrightarrow{a_1} s \xrightarrow{b_2} t \) and \( s_0 \xrightarrow{b_1} s' \xrightarrow{a_2} t \), with \( s, s' \) final, meaning if (AC2) holds that \( t \) is final, a contradiction. Finally, to test (LC3), we again implement \( L \) into an \( AA \) and test if \( S(AA) \) satisfies (AC3). As described in the proof of Theorem 11, if \( L(A) \) satisfies (LC3), then \( S(AA) \) satisfies (AC3). Conversely, if \( S(AA) \) satisfies (AC3), the proof also shows that \( L(A) \) satisfies (LC3). This gives a PSPACE algorithm. The complexity is polynomial if \( P \) is not part of the input and \( A \) is deterministic.

Note that while the algorithms to test for (LC1), (LC2), (LC3) may be PSPACE, they are actually polynomial in the size of the asynchronous automaton \( AA \) we want to obtain. As shown below, obtaining the global state space for \( AA \) is actually feasible in a number of examples, and hence testing for (LC1), (LC2) and (LC3) is also doable in these cases.

5 Experiments

In this section, we report our experiments on the implementation of the results in this paper, based on the construction from [8], which has not been implemented before. To give a point of comparison, we also report results obtained using the only previous implementation prototype for Zielonka constructions from [22], which implements the original synthesis algorithms from [23] and the heuristic in [22].

We report below the results of several systems that are (distributively) implemented using these three algorithms: We will denote by \( \text{heuristic} \) the heuristic from [22], by \( \text{original} \) the original Zielonka’s construction from [23], and by \( \text{local} \) and \( \text{global} \) two different metrics for our new implementation as described below. \( \text{heuristic} \) takes into account the structure of the automaton (using ideas from the theory of regions [17]) to identify small asynchronous automata before generating the whole global state space. Since such structural properties cannot be found for every regular commutation-closed language, it uses the equivalence in \( \text{original} \) as an upper bound. Hence, the state space produced by \( \text{heuristic} \) is never bigger than the one of \( \text{original} \). On the other hand, \( \text{original} \) uses a generic construction which always produces an asynchronous automaton. In contrast to these two algorithms producing global state spaces, our implementation produces the local state space directly. Further, ours is an on-the-fly symbolic algorithm. As argued in [20], on-the-fly computation allows to implement distributed algorithms whose global state space cannot be explicitly enumerated: with 4 processes, the timestamping used in [23, 8] can give rises to \( 10^7 \) global states, and to \( 10^{16} \) global states with 5 processes. But for symbolic algorithms (e.g., the one from [8] that we implement), 5 processes means maintaining 128 bits of information, which can be updated in time polynomial in the number of bits. To produce and compare the results of all algorithms, we report global state spaces, thus limiting ourselves to less than 4 processes.

The results are compiled in the table below. The first column gives the names of the input systems, while second and third provide their number of states \( |A| \) and processes \( |P| \), respectively. The fourth column states the syntactical properties (ACi) of the automaton \( A \). The next three columns give the number of global states produced by each of the algorithms. As noted earlier, the new prototype does not need to compute the global state space, unlike [22, 23]. The column \( \text{local} \) reports the total number of local states generated by our algorithm, which is closer to what would be used in practice (but is still larger than what is explored on-the-fly). The last row describes the properties (DF for deadend-free, LA for locally accepting, LE for locally enabled, and R for realistic) of the obtained asynchronous automaton using the new implementation, all being deterministic.

The first four systems come directly from distributed algorithms: a mutual exclusion protocol with semaphores with 2 different distribution alphabets referred to as \text{mutex-a} and \text{mutex-b}; a simple program with 3 processes denoted \text{simple}; and a dining philosopher.
protocol phil. All these examples except simple, from [22], satisfy AC1,AC2,AC3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>satisfies</th>
<th>heuristic</th>
<th>original</th>
<th>global</th>
<th>local</th>
<th>satisfies</th>
</tr>
</thead>
<tbody>
<tr>
<td>mutex-a</td>
<td>13</td>
<td>3</td>
<td>(AC1,AC2,AC3)</td>
<td>13</td>
<td>1493</td>
<td>271</td>
<td>126</td>
<td>(R)</td>
</tr>
<tr>
<td>mutex-b</td>
<td>14</td>
<td>4</td>
<td>(AC1,AC2,AC3)</td>
<td>14</td>
<td>34</td>
<td>22</td>
<td>16</td>
<td>(R)</td>
</tr>
<tr>
<td>simple</td>
<td>3</td>
<td>3</td>
<td>(AC1,AC2)</td>
<td>5</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>(DF+LA)</td>
</tr>
<tr>
<td>phil</td>
<td>5</td>
<td>4</td>
<td>(AC1,AC2,AC3)</td>
<td>5</td>
<td>70</td>
<td>71</td>
<td>60</td>
<td>(R)</td>
</tr>
<tr>
<td>prop2</td>
<td>6</td>
<td>2</td>
<td>(AC2)</td>
<td>188</td>
<td>188</td>
<td>36</td>
<td>21</td>
<td>(LA+LE)</td>
</tr>
<tr>
<td>prop3</td>
<td>11</td>
<td>3</td>
<td>(AC2)</td>
<td>639</td>
<td>639</td>
<td>240</td>
<td>92</td>
<td>(LA+LE)</td>
</tr>
<tr>
<td>L4</td>
<td>8</td>
<td>2</td>
<td>(AC1,AC3) + (LC2)</td>
<td>N/A</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>(R)</td>
</tr>
</tbody>
</table>

For these first 4 systems, the new prototype gives an implementation with lesser states than original (up to 10 times), although not as good as heuristic. Adapting ideas from heuristic [22] might reduce the size of the produced implementation. The two systems propN correspond to a distributed supervisor which detects whether a critical section has been accessed by 2 processes in parallel among N processes. On each process, it observes entry and exit of the critical section and synchronization between processes, and detects if a process which enters the critical section has been informed that other processes have exited it. This supervisor works on any possible (correct or not) mutual exclusion protocol, and detects on-the-fly whether the critical section was accessed by 2 processes concurrently. On this example, heuristic does not do better than original. The number of local states is around 8 times smaller, while global states are around 4 times smaller than previous implementations. As (LC1) does not hold, a realistic implementation is not possible here.

Notice that heuristic is guaranteed to return correct results only when all states are final [22], which is the case for the first 6 systems. The last system we experiment on is the minimal automaton L4 for language L4 from the previous section (L4 does not satisfy (AC2), although L4 satisfies (LC2)). Some states of this automaton are not final and the implementation created by heuristic is incorrect: its language is strictly larger than L4. On the other hand, implementations produced by original and the new prototype accept exactly L4. Details on the experiments can be found online at: http://is.gd/fsttcs13_benchmark.

6 Related Work and Conclusion

In this paper, we have provided syntactical and semantical characterizations of languages corresponding to several variants of realistic asynchronous automata. We designed algorithms to obtain the distributed implementation, test for the different characterizations and showed their experimental effectiveness. Our results subsume past results and answer several open questions. Corollary 17 subsumes what was claimed in [17] and proved in [22] (Theorem 2) in the subcase where the language is prefix closed. It is also worth mentioning that [1] had introduced the notion of causal closure for Message Sequence Graphs, which are a distributed model using message passing for communication. Our notion of causal closure is directly adapted from theirs. However, unlike in Corollary 18, only one direction was proved for their model. Also, they lack the syntactical characterization using (AC2) which holds by Theorem 11. Also, Corollary 18 answers an open question in the conclusion of [2].

As future work, it would be interesting to consider alternative ways of inputing the language, e.g., by giving a set of representatives to represent the language. This would avoid starting from a large automaton, and may lead to a smaller distributed implementation.

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References


