Expressiveness modulo Bisimilarity of Regular Expressions with Parallel Composition

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The languages accepted by finite automata are precisely the languages denoted by regular expressions. In contrast, finite automata may exhibit behaviours that cannot be described by regular expressions up to bisimilarity. In this paper, we consider extensions of the theory of regular expressions with various forms of parallel composition and study the effect on expressiveness. First we prove that adding pure interleaving to the theory of regular expressions strictly increases its expressiveness modulo bisimilarity. Then, we prove that replacing the operation for pure interleaving by ACP-style parallel composition gives a further increase in expressiveness, still insufficient, however, to facilitate the expression of all finite automata up to bisimilarity. Finally, we prove that the theory of regular expressions with ACP-style parallel composition and encapsulation is expressive enough to express all finite automata up to bisimilarity. Our results extend the expressiveness results obtained by Bergstra, Bethke and Ponse for process algebras with (the binary variant of) Kleene’s star operation.

1. Introduction

A well-known theorem by Kleene states that the languages accepted by finite automata are precisely the languages denoted by regular expressions (see, e.g., the textbook by Hopcroft, Motwani & Ullman (2006)). Milner (1984) showed how regular expressions can be used to describe behaviour by directly associating finite automata with them. He then observed that the process-theoretic counterpart of Kleene’s theorem — stating that every finite automaton is described by a regular expression — fails: there exist finite automata whose behaviours cannot faithfully, i.e., up to bisimilarity, be described by
regular expressions. Baeten, Corradini & Grabmayer (2007) found a structural property on finite automata that characterises those that are denoted with a regular expression modulo bisimilarity. In this paper, we study to what extent the expressiveness of regular expressions increases when various forms of parallel composition are added.

Our first result is to show that adding an operation for pure interleaving to regular expressions strictly increases their expressiveness modulo bisimilarity. A crucial step in our proof consists of characterising the strongly connected components in finite automata denoted by regular expressions. The characterisation allows us to prove a property pertaining to the exit transitions from such strongly connected components. If interleaving is added, then it is possible to denote finite automata violating this property.

Our second result is to show that replacing the operation for pure interleaving by ACP-style parallel composition of Bergstra & Klop (1984), which implements a form of synchronisation by communication between components, leads to a further increase in expressiveness. To this end, we first characterise the strongly connected components in finite automata denoted by regular expressions with interleaving, and deduce a property on the exit transitions from such strongly connected components. Then, we present an expression in the theory of regular expressions with ACP-style parallel composition that denotes a finite automaton violating this property.

Our third result is to show that the theory of regular expressions extended with ACP-style parallel composition, but not including encapsulation, is not expressive enough to denote all finite automata.

Our fourth result is to establish that adding ACP-style parallel composition and encapsulation to the theory of regular expressions actually yields a theory in which every finite automaton can be expressed up to isomorphism, and hence, since bisimilarity is coarser than isomorphism, also up to bisimilarity. Every expression in the resulting theory, in turn, denotes a finite automaton, so this result can be thought of as an alternative process-theoretic counterpart of Kleene’s theorem.

The results in this paper are inspired by the results of Bergstra, Bethke & Ponse (1994) pertaining to the relative expressiveness of process algebras with a binary variant of Kleene’s star operation. They establish an expressiveness hierarchy on the extensions of the process theories BPA(\(A\)), BPA\(\delta\)(\(A\)), PA(\(A\)), PA\(\delta\)(\(A\)), ACP(\(A, \gamma\)), and ACP\(\tau\)(\(A, \gamma\)) with binary Kleene star. The reason that their results are based on extensions with the binary version of the Kleene star is that they want to avoid the process-theoretic complications arising from the notion of intermediate termination (a state in a finite automaton is intermediately terminating if it is terminating but also admits a transition). Most of the expressiveness results of Bergstra et al. (1994) are included in (Bergstra, Fokkink & Ponse 2001), with more elaborate proofs.

For a comparison of our results with the results of Bergstra et al. (1994) and Bergstra et al. (2001), we first cast our contributions in process-theoretic terminology: regular expressions are the expressions of BPA\(\delta_{0,1}(A)\), regular expressions extended with pure interleaving are the expressions of PA\(\delta_{0,1}(A)\), regular expressions extended with ACP-style parallel composition, but without encapsulation, are the expressions of ACP\(\delta_{0,1}(A, \gamma)\), and regular expressions extended with ACP-style parallel composition and encapsulation are the expressions of ACP\(\tau_{0,1}(A, \gamma)\). Our results then establish a strict relative
expressiveness hierarchy on the process theories $\text{BPA}_{\delta}^0(A)$, $\text{PA}_{\delta}^0(A)$, $\text{ACP}_{\delta}^0(A, \gamma)$, and $\text{ACP}_{\delta}^0(A, \gamma)$, modulo bisimilarity.

The differences between the process theories $\text{BPA}_{\delta}(A)$, $\text{PA}_{\delta}(A)$ and $\text{ACP}(A, \gamma)$ considered by Bergstra et al. (1994) and Bergstra et al. (2001) on the one hand, and the process theories $\text{BPA}_{\delta}^0(A)$, $\text{PA}_{\delta}^0(A)$, $\text{ACP}_{\delta}^0(A, \gamma)$ and $\text{ACP}_{\delta}^0(A, \gamma)$ considered in this paper on the other hand are as follows: we write $0$ for the constant deadlock which is denoted by $\delta$ in (Bergstra et al. 1994, Bergstra et al. 2001), we include the unary Kleene star instead of its binary variant, and we include a constant $1$ denoting the successfully terminated process. The first difference is, of course, cosmetic, and with the addition of the constant $1$ the unary and binary variants of Kleene’s star are interdefinable. So, our results pertaining to the relative expressiveness of $\text{BPA}_{\delta}^0(A)$, $\text{PA}_{\delta}^0(A)$, $\text{ACP}_{\delta}^0(A, \gamma)$ and $\text{ACP}_{\delta}^0(A, \gamma)$ extend the expressiveness hierarchy of Bergstra et al. (1994) and Bergstra et al. (2001) with the constant $1$.

The paper is organised as follows. In Section 2 we present the process theory $\text{ACP}_{\delta}^0(A, \gamma)$, and its subtheories $\text{ACP}_{\delta}^0(A, \gamma)$, $\text{PA}_{\delta}^0(A)$, and $\text{BPA}_{\delta}^0(A)$. In Section 3 we provide a characterisation of the strongly connected components in the subtheories $\text{ACP}_{\delta}^0(A, \gamma)$, $\text{PA}_{\delta}^0(A)$ and $\text{BPA}_{\delta}^0(A)$. In Section 4 we prove that $\text{PA}_{\delta}^0(A)$ is more expressive than $\text{BPA}_{\delta}^0(A)$. In Section 5 we prove that $\text{ACP}_{\delta}^0(A, \gamma)$, by which we denote $\text{ACP}_{\delta}^0(A, \gamma)$ without encapsulation, is more expressive than $\text{PA}_{\delta}^0(A)$. In Section 6 we prove that $\text{ACP}_{\delta}^0(A, \gamma)$ is more expressive than $\text{ACP}_{\delta}^0(A, \gamma)$. In Section 7 we prove that every finite automaton is denoted, up to isomorphism, by an $\text{ACP}_{\delta}^0(A, \gamma)$ expression. We end the paper in Section 8 with some conclusions.

An extended abstract of this article without proofs and without the results of Section 6 has already appeared in the proceedings of EXPRESS 2010 edited by Fröschle & Valencia (2010).

2. Regular Expressions with $\text{ACP}(A, \gamma)$-style parallel composition and encapsulation

In this section, we present the relevant definitions for the process theory $\text{ACP}_{\delta}^0(A, \gamma)$ and its subtheories $\text{ACP}_{\delta}^0(A, \gamma)$, $\text{PA}_{\delta}^0(A)$, and $\text{BPA}_{\delta}^0(A)$. We give their syntax and operational semantics, and the notion of (strong) bisimilarity. We also introduce some auxiliary technical notions that we need in the remainder of the paper. The expressions of the process theory $\text{BPA}_{\delta}^0(A)$ are precisely the well-known regular expressions, but we shall consider the automata associated with them modulo bisimilarity instead of modulo language equivalence.

The process theory $\text{ACP}_{\delta}^0(A, \gamma)$ is parameterised by a non-empty set $A$ of actions, and a communication function $\gamma$ on $A$, i.e., an associative and commutative binary partial operation $\gamma : A \times A \to A$. $\text{ACP}_{\delta}^0(A, \gamma)$ incorporates a form of synchronisation between the components of a parallel composition by allowing certain actions to engage in a communication resulting in another action. The communication function $\gamma$ then defines which actions may communicate and what is the result. The details of this feature will become clear when we present the operational semantics of parallel composition.

The set of $\text{ACP}_{\delta}^0(A, \gamma)$ expressions $\mathcal{P}_{\text{ACP}_{\delta}^0(A, \gamma)}$ is generated by the following gram-
An expression of the form $p$ event of sending some datum $d$ transition labelled with $\gamma$ cation function labelled with components: if one of the components of a parallel composition can execute a transition in rule 15 is employed to model a form of communication between parallel style of Structural Operational Semantics (Plotkin (2004)). Note how the communicates. The operational rules listed in Table 1 formalise the operational behaviour in the result.

The constants $0$ and $1$ respectively stand for the deadlocked process and the successfully terminated process, and the constants $a \in A$ denote processes of which the only behaviour is to execute the action $a$ and then successfully terminate. An expression of the form $p \cdot q$ is called a sequential composition, an expression of the form $p + q$ is called an alternative composition, and an expression of the form $p^*$ is called a star expression. An expression of the form $p \parallel q$ is called a parallel composition, and an expression of the form $\partial H(p)$ is called an encapsulation.

The process theory $ACP(A, \gamma)$ (excluding the constants $0$ and $1$, but including a constant $\delta$ with exactly the same behaviour as $0$, and without the operation $\gamma$) originates with Bergstra & Klop (1984). The extension of $ACP(A, \gamma)$ with a constant denoting the successfully terminated process was investigated by Koymans & Vrancken (1985), Baeten & van Glabbeek (1987), Vrancken (1997), and by Baeten, Basten & Reniers (2010) (in the first three works, the constant was denoted $\varepsilon$). The extension of $ACP(A, \gamma)$ with the binary version of the Kleene star was first proposed by Bergstra et al. (1994). The reader already familiar with the process theory $ACP_{\ast 1}(A, \gamma)$ will have noticed that the operations $\parallel$ (left merge) and $| \cdot$ (communication merge) are missing from our syntax definition. Bergstra & Klop (1984) included these operations as auxiliary operations necessary for a finite axiomatisation of the theory. They do not, however, add expressiveness in our setting with Kleene star instead of a general form of recursion (see Appendix A for the proof of this fact); we have omitted them to achieve a more efficient presentation of our results.

From the names for the constructions in the syntax of $ACP_{\ast 1}(A, \gamma)$, the reader probably has already an intuitive understanding of the behaviour of the corresponding processes. The operational rules listed in Table 1 formalise the operational behaviour in the style of Structural Operational Semantics (Plotkin (2004)). Note how the communication function in rule 15 is employed to model a form of communication between parallel components: if one of the components of a parallel composition can execute a transition labelled with $a$, the other can execute a transition labelled with $b$, and the communication function $\gamma$ is defined on $a$ and $b$, then the parallel composition can execute a transition labelled with $\gamma(a, b)$. (It may help to think of the action $a$ as standing for the event of sending some datum $d$, the action $b$ as standing for the event of receiving datum $d$, and the action $\gamma(a, b)$ as standing for the event that two components communicate datum $d$.) The $A$-labelled transition relation $\rightarrow_{ACP_{\ast 1}(A, \gamma)}$ and the termination relation $\downarrow_{ACP_{\ast 1}(A, \gamma)}$ on $P_{ACP_{\ast 1}(A, \gamma)}$ are the least relations $\rightarrow \subseteq P_{ACP_{\ast 1}(A, \gamma)} \times A \times P_{ACP_{\ast 1}(A, \gamma)}$ and $\downarrow \subseteq P_{ACP_{\ast 1}(A, \gamma)}$ satisfying the rules in Table 1. The triple

$$T_{ACP_{\ast 1}(A, \gamma)} = (P_{ACP_{\ast 1}(A, \gamma)}, \rightarrow_{ACP_{\ast 1}(A, \gamma)}, \downarrow_{ACP_{\ast 1}(A, \gamma)})$$

consisting of the $ACP_{\ast 1}(A, \gamma)$ expressions together with the $A$-labelled transition relation and the termination predicate associated with them, is an example of an $A$-labelled
transition system space. In general, an A-labelled transition system space \((S, \rightarrow, \downarrow)\) consists of a (non-empty) set \(S\), the elements of which are called states, together with an A-labelled transition relation \(\rightarrow \subseteq S \times A \times S\) and a subset \(\downarrow \subseteq S\). We shall in this paper consider three more examples of transition system spaces, obtained by restricting the syntax of \(\text{ACP}_0^{*}(A, \gamma)\) and making special assumptions about the communication function.

Firstly, we define the A-labelled transition system space

\[
\mathcal{T}_{\text{ACP}_0^{*}(A, \gamma)} = (\mathcal{P}_{\text{ACP}_0^{*}(A, \gamma)}, \rightarrow, \downarrow_{\text{ACP}_0^{*}(A, \gamma)}, \downarrow_{\text{ACP}_0^{*}(A, \gamma)})
\]

corresponding with the process theory \(\text{ACP}_0^{*}(A, \gamma)\). The set of \(\text{ACP}_0^{*}(A, \gamma)\) expressions \(\mathcal{P}_{\text{ACP}_0^{*}(A, \gamma)}\) consists of the \(\text{ACP}_0^{*}(A, \gamma)\) process expressions without occurrences of the construct \(\partial_H\). The \(\text{ACP}_0^{*}(A, \gamma)\) transition relation \(\rightarrow_{\text{ACP}_0^{*}(A, \gamma)}\) on \(\mathcal{P}_{\text{ACP}_0^{*}(A, \gamma)}\) and the termination predicate \(\downarrow_{\text{ACP}_0^{*}(A, \gamma)}\) on \(\mathcal{P}_{\text{ACP}_0^{*}(A, \gamma)}\) are the transition relation and termination predicate induced on \(\text{ACP}_0^{*}(A, \gamma)\) expressions by the operational rules in Table 1 minus the rules 16–17.

Secondly, we define the A-labelled transition system space

\[
\mathcal{T}_{\text{PA}_0^{*}(A)} = (\mathcal{P}_{\text{PA}_0^{*}(A)}, \rightarrow, \downarrow_{\text{PA}_0^{*}(A)}, \downarrow_{\text{PA}_0^{*}(A)})
\]

corresponding with the process theory \(\text{PA}_0^{*}(A)\). The set of \(\text{PA}_0^{*}(A)\) expressions \(\mathcal{P}_{\text{PA}_0^{*}(A)}\) consists of the \(\text{ACP}_0^{*}(A, \gamma)\) process expressions without occurrences of the construct \(\partial_H\). The \(\text{PA}_0^{*}(A)\) transition relation \(\rightarrow_{\text{PA}_0^{*}(A)}\) on \(\mathcal{P}_{\text{PA}_0^{*}(A)}\) and the termination predicate \(\downarrow_{\text{PA}_0^{*}(A)}\) on \(\mathcal{P}_{\text{PA}_0^{*}(A)}\) are the transition relation and termination predicate induced on \(\text{PA}_0^{*}(A)\) expressions by the operational rules in Table 1 minus the rules 15–17.

Alternatively (and equivalently) the transition relation \(\rightarrow_{\text{PA}_0^{*}(A)}\) can be defined as the restriction of the transition relation \(\rightarrow_{\text{ACP}_0^{*}(A, \emptyset)}\), with \(\emptyset\) denoting the communication function that is everywhere undefined, to \(\mathcal{P}_{\text{PA}_0^{*}(A)}\).

Thirdly, we define the A-labelled transition system space

\[
\mathcal{T}_{\text{BPA}_0^{*}(A)} = (\mathcal{P}_{\text{BPA}_0^{*}(A)}, \rightarrow, \downarrow_{\text{BPA}_0^{*}(A)}, \downarrow_{\text{BPA}_0^{*}(A)})
\]

associated with the process theory \(\text{BPA}_0^{*}(A)\). Let \(\mathcal{P}_{\text{BPA}_0^{*}(A)}\) consist of all \(\text{PA}_0^{*}(A)\)
expressions without occurrences of the construct **. The BPA
2 If p obtained by restricting −−→ that
moreover, immediate from the operational rules that if p exists
−−→ s that
∈A
J. C. M. Baeten, B. Luttik, T. Muller, and P. J. A. van Tilburg
Lemma 2.2. The transition system spaces ACP

1 If p exist
−−→ s such that
∈A
It is immediate from the operational rules that if p exists
−−→ s such that
∈A
−−→ s∗ that
∈A
The following lemma records some straightforward consequences of the operational
Proof. By induction on the maximal depth of *-nestings it can be established for every
p in the respective transition system spaces that the set [p]→ is finite (see also (Bergstra
et al. 1994, Lemma 3.1)).

The following lemma records some straightforward consequences of the operational
rules that will turn out to be useful in the technical developments to follow.

Lemma 2.2. Let p, q and r be ACP
• expressions.
1 If p • q −→* r, then there exists an ACP
• expression p′ such that p −→* p′ and
either r = p′ • q or p′ ↓ and q −→* r.
2 If p • q′ −→* r, then there exists an ACP
• expression p′ such that p −→* p′
and r = p′ • q′, or there exist ACP
• expressions p′ and q′ such that p −→* p′,
p′ ↓, q −→* q′, and r = q′ • q′.
3 If p • q −→* r, then there exist ACP
• expressions p′ and q′ such that r = p′ • q′,
p −→* p′ and q −→* q′.

Proof. It is immediate from the operational rules that if p • q −→ r, then either there
exists p′ such that p −→ p′ and r = p′ • q, or p↓ and q −→ r. In the latter case it is,
moreover, immediate from the operational rules that if q = (q′)∗ for some ACP
• (A, γ) expression q′, then there exists q′′ such that q′ −→ q′′ and r = q′′ • (q′)∗. Finally, it is also
immediate from the operational rules that if p • q −→ r, then either there exists p′ such
that p −→ p′ and r = p′ • q, or there exists q′ such that q −→ q′ and r = p • q′, or there
exist p′ and q′ such that p −→ p′, q −→ q′ and r = p′ • q′. From these observations, the
lemma follows with a straightforward induction on the lengths of transitions sequences
from p • q, p • q∗ and p • q to r, respectively.
We say that a state $s$ is normed if there exists $s'$ such that $s \rightarrow^* s'$ and $s' \downarrow$.

**Lemma 2.3.** Let $p$ and $q$ be process expressions. Then

1. $p \cdot q$ is normed iff $p$ and $q$ are both normed; and
2. $p \parallel q$ is normed iff $p$ and $q$ are both normed.

**Proof.** Suppose that $p$ and $q$ are both normed. Then there exists $p'$ such that $p \rightarrow^* p'$ and $p' \downarrow$, and there exists $q'$ such that $q \rightarrow^* q'$ and $q' \downarrow$.

With a straightforward induction on the sum of the lengths of a transition sequences from $p$ to $p'$ and $q$ to $q'$, it follows from rules 7 and 8 that either $p \cdot q \rightarrow^* p' \cdot q'$ (if the length of the transition sequence from $q$ to $q'$ is zero), or $p \cdot q \rightarrow^* q'$ (if the length of the transition sequence from $q$ to $q'$ is non-zero), and $p' \cdot q' \downarrow$ follows from rule 9 and $q' \downarrow$ holds by assumption. Hence, $p \cdot q$ is normed.

With a similar induction it follows from rules 12 and 13 that $p \parallel q \rightarrow^* p' \parallel q'$. Moreover, from rule 14 it follows that $p' \parallel q' \downarrow$. Hence $p \parallel q$ is normed.

Suppose that $p \cdot q$ is normed. Then there exists $r$ such that $p \cdot q \rightarrow^* r$ and $r \downarrow$. So, by Lemma 2.2, either there exists $p'$ such that $p \rightarrow^* p'$ and $r = p' \cdot q$, or there exist $p'$ and $q'$ such that $p \rightarrow^* p'$, $p' \downarrow$, and $q \rightarrow^* r$. In the first case, from $r = p' \cdot q$ and $p' \downarrow$, it follows, according to the operational rules in Table 1, that $p' \downarrow$ and $q', r$ and hence $p$ and $q$ are both normed. In the second case, since $p' \downarrow$ and $r' \downarrow$, it also follows that $p$ and $q$ are both normed.

Suppose that $p \parallel q$ is normed. Then, there exists $r$ such that $p \cdot q \rightarrow^* r$ and $r \downarrow$, and hence, by Lemma 2.2, there exist $p'$ and $q'$ such that $p \rightarrow^* p'$, $q \rightarrow^* q'$ and $r = p' \parallel q'$. From $r \downarrow$ it follows, according to the operational rules in Table 1, that $p' \downarrow$ and $q' \downarrow$. Hence, $p$ and $q$ are both normed.

With every state $s$ in $T$ we can associate an automaton (or: transition system)

$$(\{s\} \rightarrow, \rightarrow \cap (\{s\} \times A \times \{s\} \rightarrow), \downarrow \cap \{s\} \rightarrow, s)$$

Its states are the states reachable from $s$, its transition relation and termination predicate are obtained by restricting $\rightarrow$ and $\downarrow$ accordingly, and the state $s$ is declared as the initial state of the automaton. If a transition system space is regular, then the automaton associated with a state in it is finite, i.e., it is a finite automaton in the terminology of automata theory. Thus, we get by Lemma 2.1 that the operational semantics of $ACP_{0,1}(A, \gamma)$, and, a fortiori, of $ACP_{0,1}^*(A, \gamma)$, $PA_{0,1}(A)$ and $BPA_{0,1}(A)$, associates a finite automaton with every process expression.

In automata theory, automata are usually considered as language acceptors and two automata are deemed indistinguishable if they accept the same languages. Language equivalence is, however, arguably too coarse in process theory, where the prevalent notion is bisimilarity (Milner 1989, Park 1981).

**Definition 2.4.** Let $T_1 = (S_1, \rightarrow_1, \downarrow_1)$ and $T_2 = (S_2, \rightarrow_2, \downarrow_2)$ be transition system spaces. A binary relation $R \subseteq S_1 \times S_2$ is a bisimulation between $T_1$ and $T_2$ if it satisfies, for all $a \in A$ and for all $s_1 \in S_1$ and $s_2 \in S_2$ such that $s_1 \parallel s_2$, the following conditions:
— if there exists $s_1' \in S_1$ such that $s_1 \xrightarrow{a_1} s_1'$, then there exists $s_2' \in S_2$ such that $s_2 \xrightarrow{a_2} s_2'$ and $s_1' \mathcal{R} s_2'$;
— if there exists $s_2' \in S_2$ such that $s_2 \xrightarrow{a_2} s_2'$, then there exists $s_1' \in S_1$ such that $s_1 \xrightarrow{a_1} s_1'$ and $s_1' \mathcal{R} s_2'$; and
— $s_1 \downarrow_1$ if, and only if, $s_2 \downarrow_2$.

States $s_1 \in S_1$ and $s_2 \in S_2$ are bisimilar (notation: $s_1 \leftrightarrow s_2$) if there exists a bisimulation $\mathcal{R}$ between $T_1$ and $T_2$ such that $s_1 \mathcal{R} s_2$.

To achieve a sufficient level of generality, we have defined bisimilarity as a relation between transition system spaces; to obtain a suitable notion of bisimulation between automata one should add the requirement that the initial states of the automata be related.

Based on the associated transition system spaces, we can now define what we mean when some transition system space is, modulo bisimilarity, less expressive than some other transition system space.

**Definition 2.5.** Let $T_1$ and $T_2$ be transition system spaces. We say that $T_1$ is less expressive than $T_2$ (notation: $T_1 \prec T_2$) if every state in $T_1$ is bisimilar to a state in $T_2$, and, moreover, there is a state in $T_2$ that is not bisimilar to some state in $T_1$.

When we investigate the expressiveness of $\text{ACP}^*_{0,1}(A, \gamma)$, we want to be able to choose $\gamma$. So, we are actually interested in the expressiveness of the (disjoint) union of all transition system spaces $\text{ACP}^*_{0,1}(A, \gamma)$ with $\gamma$ ranging over all communication functions; we denote this transition system space by $\bigcup \gamma \text{ACP}^*_{0,1}(A, \gamma)$. Similarly, we denote by $\bigcup \gamma \text{ACP}^*_{0,1}^{-\partial}(A, \gamma)$ the (disjoint) union of all transition system spaces $\text{ACP}^*_{0,1}^{-\partial}(A, \gamma)$ with $\gamma$ ranging over all communication functions. In this paper we shall establish that

$$\text{BPA}^*_{0,1}(A) \prec \text{PA}^*_{0,1}(A) \prec \bigcup \gamma \text{ACP}^*_{0,1}^{-\partial}(A, \gamma) \prec \bigcup \gamma \text{ACP}^*_{0,1}(A, \gamma).$$

**Remark 2.6.** Gorla (2010) proposed a set of general criteria for comparing the relative expressiveness of process calculi. There are two assumptions in his work that preclude its application in our setting. First, Gorla (2010) presupposes that the compared calculi both include a notion of parallel composition; this would exclude $\text{BPA}^*_{0,1}(A)$ from consideration. Second, the criteria formulated by Gorla (2010) are based on (the transitive-reflexive closure) of a reduction relation on expressions. Such a reduction relation naturally arises in a calculus in which the result of synchronisation between processes is considered unobservable (i.e., is semantically modelled as a transition labelled with the special unobservable $\tau$). In the process calculi we consider, however, there is no notion of unobservability; our results are up to strong bisimilarity.

### 3. Strongly Connected Components

A crucial step in establishing the strictness of the aforementioned expressiveness hierarchy will be to characterise the strongly connected components in the respective transition system spaces. First, we recall below the notion of strongly connected component. Then
we shall provide an inductive characterisation of the strongly connected components in $\text{ACP}_{0,1}^*(A,\gamma)$, $\text{PA}_{0,1}^*(A)$, and $\text{BPA}_{0,1}^*(A)$.

**Definition 3.1.** A strongly connected component in a transition system space $T = (S, \rightarrow, \downarrow)$ is a maximal subset $C$ of $S$ such that $s \rightarrow * s'$ for all $s, s' \in C$. A strongly connected component $C$ is trivial if it consists of only one state, say $C = \{s\}$, and $s \not\rightarrow s$; otherwise, it is non-trivial.

Note that every state of a transition system space is in precisely one strongly connected component of that space. Furthermore, if $s$ is a state of a non-trivial strongly connected component, then $s \rightarrow + s$. Since in a strongly connected component from every state every other state can be reached, we get as a corollary to Lemma 2.1 that strongly connected components in $\text{ACP}_{0,1}^*(A,\gamma)$, $\text{ACP}_{0,1}^*(A,\gamma)$, $\text{PA}_{0,1}^*(A)$ and $\text{BPA}_{0,1}^*(A)$ are finite.

Let $T = (S, \rightarrow, \downarrow)$ be a transition system space, let $s \in S$, and let $C \subseteq S$ be a strongly connected component in $S$. We say that $C$ is reachable from $s$ if $s \rightarrow * s'$ for some $s' \in C$; clearly, this means that $s \rightarrow * s'$ for all $s' \in C$.

**Lemma 3.2.** Let $T_1 = (S_1, \rightarrow_1, \downarrow_1)$ and $T_2 = (S_2, \rightarrow_2, \downarrow_2)$ be regular transition system spaces, and let $s_1 \in S_1$ and $s_2 \in S_2$ be such that $s_1 \not\equiv s_2$. If $s_1$ is an element of a strongly connected component $C_1$ in $T_1$, then there exists a strongly connected component $C_2$ reachable from $s_2$ satisfying that for all $s'_1 \in C_1$ there exists $s'_2 \in C_2$ such that $s'_1 \equiv s'_2$.

**Proof.** According to Lemma 2.1, the set $[s_2]_\rightarrow$ is finite; we use induction on $|[s_2]_\rightarrow|$. Let $C_1$ be the strongly connected component in $T_1$ that contains $s_1$. If the unique strongly connected component $C_2$ in $T_2$ containing $s_2$ is such that for all $s'_1 \in C_1$ there exists $s'_2 \in C_2$ such that $s'_1 \equiv s'_2$, then we are done. In particular, this is the case if $|[s_2]_\rightarrow| = 1$. Otherwise, there exists a state in $C_1$, say $s'_1$, for which there is no bisimilar state in the strongly connected component containing $s_2$, and since $s_1 \rightarrow + s'_1 \rightarrow + s_1$, it follows that there exists $s'_2$ distinct from $s_2$ such that $s_2 \rightarrow + s'_2$ and $s_1 \not\equiv s'_2$.

Clearly, $|[s'_2]_\rightarrow| < |[s_2]_\rightarrow|$, so by the induction hypothesis there exists a strongly connected component $C_2$ reachable from $s'_2$, and hence also from $s_2$, satisfying that for all $s'_1 \in C_1$ there exists $s''_2 \in C_2$ such that $s'_1 \equiv s''_2$.

We shall now establish that a non-trivial strongly connected component in the transition system space $\text{ACP}_{0,1}^*(A,\gamma)$ is either of the form

$$\{p_1 \cdot q^*, \ldots, p_n \cdot q^*\}$$

with $p_i$ ($0 \leq i \leq n$) reachable from $q$ and $\{p_1, \ldots, p_n\}$ not a strongly connected component, or of the form

$$\{p_1 \cdot q, \ldots, p_n \cdot q\}$$

where $\{p_1, \ldots, p_n\}$ is a strongly connected component, or of the form

$$\{p_1 \parallel q_1, \ldots, p_n \parallel q_n\}$$

where both $\{p_1, \ldots, p_n\}$ and $\{q_1, \ldots, q_n\}$ are strongly connected components. To this
end, we first prove, by reasoning on the basis of the operational semantics, that process expressions in a non-trivial strongly connected component are necessarily sequential compositions or parallel compositions; at the heart of the argument will be the following measure on $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expressions.

**Definition 3.3.** Let $p$ an $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expression; then $\#(p)$ is defined with recursion on the structure of $p$ by the following clauses:

- $\#(\mathbf{0}) = \#(\mathbf{1}) = 0$, and $\#(a) = 1$;
- $\#(p \cdot q) = \begin{cases} 0 & \text{if } q \text{ is a star expression} \\ \#(q) + 1 & \text{otherwise}; \end{cases}$
- $\#(p + q) = \max\{\#(p), \#(q)\} + 1$;
- $\#(p\ast) = 1$; and
- $\#(p \parallel q) = 0$.

We establish that $\#(\cdot)$ is non-increasing over transitions, and, in fact, in most cases decreases.

**Lemma 3.4.** If $p$ and $p'$ are $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expressions such that $p \rightarrow p'$, then $\#(p) \geq \#(p')$. Moreover, if $\#(p) = \#(p')$, then either $p = p_1 \cdot q$ and $p' = p_1' \cdot q$, or $p = p_1 \parallel p_2$ and $p' = p_1' \parallel p_2'$ for some $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expressions $p_1$, $p_2$, $p_1'$, $p_2'$, and $q$.

**Proof.** Let $p$ and $p'$ be $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expressions. Note that if the lemma holds in the special case that $p \rightarrow p'$, then the general case follows with a straightforward induction on the length of a transition sequence from $p$ to $p'$. In the remainder of the proof we concentrate on the special case: We prove that $p \rightarrow p'$ implies $\#(p) \geq \#(p')$, and, moreover, whenever $\#(p) = \#(p')$ then, for some $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ expressions $p_1$, $p_1'$, $p_2$, $p_2'$, $p_1$, $p_2$, $p_1'$, $p_2'$, and $q$, either $p = p_1 \cdot q$ and $p' = p_1' \cdot q$, or $p = p_1 \parallel p_2$ and $p' = p_1' \parallel p_2$ with $p_1 \rightarrow p_1'$, or $p = p_1 \parallel p_2$ and $p' = p_1' \parallel p_2'$ with $p_2 \rightarrow p_2'$ or $p = p_1 \parallel p_2, p' = p_1' \parallel p_2'$, and there exist $b, c \in A$ such that $p_1 \rightarrow b \rightarrow p_1', p_2 \rightarrow c \rightarrow p_2'$ and $\gamma(b, c)$ is defined.

Let $a \in A$ be such that $p \rightarrow a \rightarrow p'$; we reason by induction on a derivation according to the operational rules for $\text{ACP}_{\text{0.1}}^{*, \gamma}(A, \gamma)$ (rules 1–15) of the transition $p \rightarrow a \rightarrow p'$. We distinguish cases according to which rule is applied last in such a derivation. (Clearly, since the rules 1, 5, 6, 9, 11, and 14 do not have a transition as a conclusion, we need not consider them.)

1. Suppose that the last rule applied is rule 2; then $p = a$ and $p' = 1$, so $\#(p) = 1 \geq 0 = \#(p')$.
2. Suppose that the last rule applied is rule 3. Then there exist $p_1$ and $p_2$ such that $p = p_1 \parallel p_2$ and $p_1 \rightarrow p'$. Since there is a derivation of $p_1 \rightarrow p'$ that is a proper subderivation of the considered derivation of $p \rightarrow p'$, it follows by the induction hypothesis that $\#(p_1) \geq \#(p')$, and hence $\#(p) = \max\{\#(p_1), \#(p_2)\} + 1 \geq \#(p_1) + 1 \geq \#(p')$.
3. If the last rule applied is rule 4, then the proof that $\#(p) > \#(p')$ is analogous to the proof in the previous case.
4. Suppose that the last rule applied is rule 7. Then there exist $p_1$, $p_1'$ and $q$ such that
Regular Expressions with Parallel Composition

$p = p_1 \cdot q$, $p_1 \xrightarrow{a} p_1'$, and $p' = p'_1 \cdot q$. There are two cases: if $q$ is a star expression then 
$\#(p) = 0 = \#(p')$, and otherwise $\#(p) = \#(q) + 1 = \#(p')$.

5 Suppose that the last rule applied is rule 8. Then there exist $p_1$ and $q$ such that 
$p = p_1 \cdot q$, with $p_1 \xrightarrow{a} q \xrightarrow{a} p'$. Note that, since there is a derivation of $q \xrightarrow{a} p'$
that is a proper subderivation of the considered derivation of $p \xrightarrow{a} p'$, we get by
the induction hypothesis that $\#(p) \geq \#(p')$. There are two subcases. On the one
hand, if $q$ is a star expression, then the last rule applied in the derivation of $q \xrightarrow{a} p'$ is
rule 10, so there exists $p_1'$ such that $p' = p'_1 \cdot q$. Since $q$ is a star expression, it
follows that $\#(p) = 0 = \#(p')$. On the other hand, if $q$ is not a star expression, then
$\#(p) = \#(q) + 1 \geq \#(p') + 1 > \#(p')$.

6 If the last rule applied is rule 10, then there exist $q$ and $q'$ such that $p = q^*, q \xrightarrow{a} q'$,
and $p' = q' \cdot q^*$. It then follows immediately from the definition of $\#(\cdot)$ that $\#(p) = 1 > \#(q' \cdot q^*)$.

7 Suppose that the last rule applied is rule 12. Then there exist $p_1$, $p'_1$ and $p_2$ such that
$p = p_1 || p_2$, $p_1 \xrightarrow{a} p'_1$, and $p' = p'_1 || p_2$, and hence $\#(p) = 0 = \#(p')$.

8 Suppose that the last rule applied is rule 13. Then there exist $p_1$, $p_2$ and $p'_2$ such that
$p = p_1 || p_2$, $p_2 \xrightarrow{a} p'_2$, and $p' = p_1 || p'_2$, and hence $\#(p) = 0 = \#(p')$.

9 Suppose that the last rule applied is rule 15. Then there exist $p_1$, $p_2$, $p'_1$, $p'_2$, $b$ and $c$,
such that $p = p_1 || p_2$, $p_1 \xrightarrow{b} p'_1$, $p_2 \xrightarrow{c} p'_2$, $p' = p'_1 || p'_2$, and $\gamma(b,c) = a$, and hence
$\#(p) = 0 = \#(p')$.

To complete the proof, we note that $\#(p) = \#(p')$ only in case 4, in the first subcase of
5, in case 7, in case 8, and in case 9, and in each of these cases the extra requirement of
the lemma is satisfied.

For a succinct presentation of the characterisation of non-trivially strongly connected
components in ACP*$_{0,1}(A,\gamma)$, it is convenient to introduce some auxiliary notation. Let
$P$ and $Q$ be sets of ACP*$_{0,1}(A,\gamma)$ expressions, and let $q$ be an ACP*$_{0,1}(A,\gamma)$ expression;
we define the sets of ACP*$_{0,1}(A,\gamma)$ expressions $P \cdot q$ and $P || Q$, respectively, by

$$
P \cdot q = \{ p \cdot q \mid p \in P \} ; \quad P || Q = \{ p || q \mid p \in P \wedge q \in Q \} .
$$

We also write $P || q$ and $p || Q$ for $P || \{ q \}$ and $\{ p \} || Q$, respectively.

**Proposition 3.5.** If $C_1$ and $C_2$ are strongly connected components in ACP*$_{0,1}(A,\gamma)$,
then $C_1 || C_2$ is also a strongly connected component in ACP*$_{0,1}(A,\gamma)$; moreover, if at
least one of $C_1$ and $C_2$ is non-trivial, then so is $C_1 || C_2$.

**Proof.** Suppose that $C_1$ and $C_2$ are strongly connected components; we need to prove
that $C_1 || C_2$ is a strongly connected component. To this end, we need to establish that
(1) $p_1 || p_2 \xrightarrow{a} p'_1 || p'_2$ for all $p_1, p'_1 \in C_1$ and $p_2, p'_2 \in C_2$, and
(2) for all ACP*$_{0,1}(A,\gamma)$ expressions $p_1, p_2, q_1$ and $q_2$ such that $p_1 || p_2 \in C_1 || C_2$,
$p_1 || p_2 \xrightarrow{a} q_1 || q_2$ and $q_1 || q_2 \notin C_1 || C_2$ it holds that $q_1 || q_2 \xrightarrow{a} p_1 || p_2$.

To prove (1), note that if $p_1, p'_1 \in C_1$ and $p_2, p'_2 \in C_2$, then, since $C_1$ and $C_2$ are strongly
connected components, we have that $p_1 \rightarrow^* p'_1$ and $p_2 \rightarrow^* p'_2$, so, according to operational rules 12 and 13, it follows that $p_1 \parallel p_2 \rightarrow^* p'_1 \parallel p'_2$.

To prove (2), note that if $q_1 \parallel q_2 \not\in C_1 \parallel C_2$, then $q_1 \not\in C_1$ or $q_2 \not\in C_2$; without loss of generality we can assume that $q_1 \not\in C_1$. Note that $p_1 \parallel p_2 \rightarrow q_1 \parallel q_2$ by Lemma 2.2(3) implies $p_1 \rightarrow q_1$. So, since $p_1 \rightarrow q_1$, $q_1 \not\in C_1$, and $C_1$ is a strongly connected component, it follows that $q_1 \not\rightarrow^* p_1$, and hence $q_1 \parallel q_2 \not\rightarrow^* p_1 \parallel p_2$.

It remains to establish that if at least one of $C_1$ and $C_2$ is non-trivial, then so is $C_1 \parallel C_2$. We proceed by contraposition. Suppose that $C_1 \parallel C_2$ is trivial. Then there exist $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $p_1$ and $p_2$ such that $C_1 \parallel C_2 = \{p_1 \parallel p_2\}$, and $p_1 \parallel p_2 \not\rightarrow p_1 \parallel p_2$. Then $C_1 = \{p_1\}$ and $C_2 = \{p_2\}$, and from $p_1 \parallel p_2 \not\rightarrow p_1 \parallel p_2$ it follows by operational rules 12 and 13 that $p_1 \not\rightarrow p_1$ and $p_2 \not\rightarrow p_2$. Hence, $C_1$ and $C_2$ are both trivial.

\textbf{Lemma 3.6.} If $C$ is a non-trivial strongly connected component in $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$, then either there exist a set of $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $C'$ and a $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expression $q$ such that $C = C' \cdot q$, or there exist strongly connected components $C_1$ and $C_2$ in $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$, at least one of them non-trivial, such that $C = C_1 \parallel C_2$.

\textit{Proof.} Let $p \in C$. Then, since $p \rightarrow^+ p$, by Lemma 3.4, either $p = p_1 \cdot q$ or $p = p_1 \parallel p_2$, for some $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $p_1$, $p_2$ and $q$. We consider these cases separately:

1 Suppose that $p = p_1 \cdot q$, and consider an arbitrary $p' \in C$. Then, since $p \rightarrow^+ p' \rightarrow^+ p$, by Lemma 3.4, $\#(p) \geq \#(p') \geq \#(p)$, so $\#(p) = \#(p')$. Therefore, again by Lemma 3.4, there exist $p'_1$ such that $p' = p'_1 \cdot q$. It follows that there exists a set of $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $C'$ such that $C = C' \cdot q$.

2 Suppose that $p = p_1 \parallel p_2$, and let $C_1$ and $C_2$ be the strongly connected components containing $p_1$ and $p_2$, respectively. We establish that $C = C_1 \parallel C_2$ and that one of $C_1$ and $C_2$ is non-trivial.

To see that $C \subseteq C_1 \parallel C_2$, consider an arbitrary $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expression $p' \in C$. Then, since $p' \rightarrow^+ p \rightarrow^+ p'$, by Lemma 2.2(3) there exist $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $p'_1$ and $p'_2$ such that $p' = p'_1 \parallel p'_2$, $p'_1 \rightarrow p_1 \rightarrow^* p_1'$, and $p'_2 \rightarrow p_2 \rightarrow^* p_2'$. It follows that $p'_1$ and $p'_2$ are in the same strongly connected components as $p_1$ and $p_2$, respectively, so $p'_1 \in C_1$ and $p'_2 \in C_2$. Hence, $p' \in C_1 \parallel C_2$. Moreover, from $p' \rightarrow^+ p'$ it can be easily deduced that either $p'_1 \rightarrow^+ p'_1$ or $p'_2 \rightarrow^+ p'_2$, so at least one of $C_1$ and $C_2$ is non-trivial.

To see that $C_1 \parallel C_2 \subseteq C$, consider an arbitrary $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expression $p' \in C_1 \parallel C_2$. Then there exist $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$ expressions $p'_1 \in C_1$ and $p'_2 \in C_2$ such that $p' = p'_1 \parallel p'_2$. Since $C_1$ is a strongly connected component containing $p_1$ and $p'_1$, we have that $p'_1 \rightarrow p_1 \rightarrow^* p_1'$, and, since $C_2$ is a strongly connected component containing $p_2$ and $p'_2$, we have that $p'_2 \rightarrow p_2 \rightarrow^* p'_2$. It follows that $p' \rightarrow^* p \rightarrow^* p'$, so $p' \in C$.

We proceed to give an inductive description of the non-trivial strongly connected components in $\text{ACP}^{* \cdot \gamma}_0(A, \gamma)$. The basis for the inductive description is the following notion of basic strongly connected component.
Definition 3.7. A non-trivial strongly connected component $C$ in $ACP_{0,1}^\star(A, \gamma)$ is basic if there exist a set of $ACP_{0,1}^\star(A, \gamma)$ expressions $C'$ and an $ACP_{0,1}^\star(A, \gamma)$ expression $q$ such that $C = C' \cdot q^*$ and $C'$ is not a strongly connected component in $ACP_{0,1}^\star(A, \gamma)$.

Proposition 3.8. Let $C$ be a non-trivial strongly connected component in $ACP_{0,1}^\star(A, \gamma)$. Then one of the following holds:

1. $C$ is a basic strongly connected component; or
2. there exist a non-trivial strongly connected component $C'$ in $ACP_{0,1}^\star(A, \gamma)$ and a $ACP_{0,1}^\star(A, \gamma)$ expression $q$ such that $C = C' \cdot q$; or
3. there exist strongly connected components $C_1$ and $C_2$ in $ACP_{0,1}^\star(A, \gamma)$, at least one of them non-trivial, such that $C = C_1 \parallel C_2$.

Proof. Let $C$ be a non-trivial strongly connected component in $ACP_{0,1}^\star(A, \gamma)$. According to Lemma 3.6 there are two cases: either there exist a set of process expressions $C'$ and a process expression $q$ such that $C = C' \cdot q$, or there exist strongly connected components $C_1$ and $C_2$, at least one of them non-trivial, such that $C = C_1 \parallel C_2$.

In the second case, there is nothing left to prove.

In the first case, we should argue that either $C$ is basic, or $C'$ is a non-trivial strongly connected component. So, suppose that $C'$ is not a non-trivial strongly connected component. Then there are $p, p' \in C'$ such that $p \not\rightarrow^+ p'$. Since $C$ is a non-trivial strongly connected component and $C = C' \cdot q$, it holds that $p \cdot q \rightarrow^+ p' \cdot q$. Using that $p \not\rightarrow^+ p'$, it can be established with induction on the length of the transition sequence from $p \cdot q$ to $p' \cdot q$ that $q \rightarrow^+ p' \cdot q$. It follows by Lemma 3.4 that $\#(q) \geq \#(p' \cdot q)$, and therefore, according to the definition of $\#(\cdot)$, $q$ must be a star expression. We conclude that $C$ is basic. \qed

Note that, in the above proposition, one of the strongly connected components $C_1$ and $C_2$ may be trivial in which case it consists of a single $ACP_{0,1}^\star(A, \gamma)$ expression.

Every $ACP_{0,1}^\star(A, \gamma)$ expression is a $PA_{0,1}^\star(A)$ expression. Moreover, although the transition relation associated with $ACP_{0,1}^\star(A, \gamma)$ does not coincide with the transition relation associated with $PA_{0,1}^\star(A)$, the relation $\rightarrow^*$ associated with $ACP_{0,1}^\star(A, \gamma)$ actually coincides with the relation $\rightarrow^*$ associated with $PA_{0,1}^\star(A)$. Hence, it immediately follows that a set of $PA_{0,1}^\star(A)$ expressions is a strongly connected component in $ACP_{0,1}^\star(A, \gamma)$ if it is a strongly connected component in $PA_{0,1}^\star(A)$. Thus, we may use Proposition 3.5 also for strongly connected components in $PA_{0,1}^\star(A)$, and Proposition 3.8 also provides a characterisation of the non-trivial strongly connected components in $PA_{0,1}^\star(A)$. For the sake of clarity, we restate both propositions for $PA_{0,1}^\star(A)$ in the following two corollaries.

Corollary 3.9. If $C_1$ and $C_2$ are strongly connected components in $PA_{0,1}^\star(A)$, then $C_1 \parallel C_2$ is also a strongly connected component in $PA_{0,1}^\star(A)$; moreover, if at least one of $C_1$ and $C_2$ is non-trivial, then so is $C_1 \parallel C_2$.

Corollary 3.10. Let $C$ be a non-trivial strongly connected component in $PA_{0,1}^\star(A)$. Then one of the following holds:

1. $C$ is a basic strongly connected component; or
there exist a non-trivial strongly connected component \( C' \) in \( \text{PA}_{0,1}^* (A) \) and a \( \text{PA}_{0,1}^* (A) \) expression \( q \) such that \( C = C' \cdot q \); or

3 there exist strongly connected components \( C_1 \) and \( C_2 \) in \( \text{PA}_{0,1}^* (A) \), at least one of them non-trivial, such that \( C = C_1 \parallel C_2 \).

Recall that \( \rightarrow_{\text{BPAP}^*_0 (A)} \) is obtained by restricting \( \rightarrow_{\text{PA}_{0,1}^* (A)} \) to \( \text{BPAP}^*_0 (A) \) expressions, which are \( \text{PA}_{0,1}^* (A) \) expressions without occurrences of \( \parallel \). It is easy to see that if \( p \) is a \( \text{BPAP}^*_0 (A) \) expression and \( p \rightarrow_{\text{PA}_{0,1}^* (A)} p' \), then \( p' \) is a \( \text{BPAP}^*_0 (A) \) expression too. Hence, if a strongly connected component in \( \text{PA}_{0,1}^* (A) \) contains a \( \text{BPAP}^*_0 (A) \) expression, then it consists entirely of \( \text{BPAP}^*_0 (A) \) expressions. We therefore obtain the following inductive characterisation of non-trivial strongly connected components in \( \text{BPAP}^*_0 (A) \) as a consequence of the preceding corollary.

**Corollary 3.11.** Let \( C \) be a non-trivial strongly connected component in \( \text{BPAP}^*_0 (A) \). Then one of the following holds:

1 \( C \) is a basic strongly connected component; or

2 there exist a non-trivial strongly connected component \( C' \) in \( \text{BPAP}^*_0 (A) \) and a \( \text{BPAP}^*_0 (A) \) expression \( q \) such that \( C = C' \cdot q \).

### 4. Relative Expressiveness of \( \text{BPAP}^*_0 (A) \) and \( \text{PA}_{0,1}^* (A) \)

Bergstra et al. (1994) prove that \( \text{BPAP}^*_0 (A) \) is less expressive than \( \text{PA}_{0,1}^* (A) \), by arguing that the \( \text{PA}_{0}^* (A) \) expression \( (a \cdot b)^* c \| d \) is not bisimilar with any \( \text{BPAP}^*_0 (A) \) expression. Bergstra et al. (2001) present an alternative and more general proof that the \( \text{PA}_{0}^* (A) \) expression above is not expressible in \( \text{BPAP}^*_0 (A) \). (Actually, the \( \text{PA}_{0}^* (A) \) expression they employ uses only a single action \( a \), i.e., considers the \( \text{PA}_{0}^* (A) \) expression \( (a \cdot a)^* a \| a \); we use the actions \( b, c \) and \( d \) for clarity.) They establish that the \( \text{PA}_{0}^* (A) \) expression above fails the following general property, which is satisfied by all \( \text{BPAP}^*_0 (A) \)-expressible automata:

If \( C \) is a cycle in an automaton associated with a \( \text{BPAP}^*_0 (A) \) expression, then there is at most one state \( p \in C \) that has an exit transition.

(A cycle is a sequence \((p_1, \ldots , p_n)\) such that \( p_i \rightarrow p_{i+1} \) (\( 1 \leq i < n \)) and \( p_n \rightarrow p_1 \); an exit transition from \( p_i \) is a transition \( p_i \rightarrow p'_i \) such that no element of the cycle is reachable from \( p'_i \).

The following example shows that automata associated with \( \text{BPAP}^*_0 (A) \) expressions do not satisfy the property above.

**Example 4.1.** Consider the automaton associated with the \( \text{BPAP}^*_0 (A) \) expression \( 1 \cdot (a \cdot (a + 1))^* \cdot b \) (see Figure 1). It has a cycle consisting of two states, and both states on the cycle have a \( b \)-transition off the cycle.

In this section we shall establish that \( \text{BPAP}^*_0 (A) \) is less expressive than \( \text{PA}_{0,1}^* (A) \). As in (Bergstra et al. 2001) we prove that \( \text{BPAP}^*_0 (A) \)-expressible automata satisfy a general property that some automaton expressible in \( \text{PA}_{0,1}^* (A) \) fails to satisfy. We find it technically convenient, however, to base our relative expressiveness proofs on the notion of
Regular Expressions with Parallel Composition

Fig. 1. A transition system in \( \text{BPA}^*_{0,1}(A) \) with a cycle with multiple exit transitions.

strongly connected component, instead of cycle. Note, e.g., that every process expression is an element of precisely one strongly connected component, while it may reside on more than one cycle. Furthermore, if \( p \rightarrow q \) and \( p \) and \( q \) are in distinct strongly connected components, then we can be sure that \( p \rightarrow q \) is an exit transition, while if \( p \) and \( q \) are on distinct cycles, then it may happen that \( p \) is reachable from \( q \).

The crucial tool that will allow us to establish that \( \text{BPA}^*_{0,1}(A) \) is less expressive than \( \text{PA}^*_{0,1}(A) \) will be a special property of states with a transition out of their strongly connected component in \( \text{BPA}^*_{0,1}(A) \). Roughly, if \( C \) is a strongly connected component in \( \text{BPA}^*_{0,1}(A) \), then all states with a transition out of \( C \) have the same transitions out of \( C \).

**Definition 4.2.** Let \( C \) be a strongly connected component in the transition system space \( T = (S, \rightarrow, \downarrow) \) and let \( s \in C \). An exit transition from \( s \) is a pair \((a, s')\) such that \( s \xrightarrow{a} s' \) and \( s' \notin C \). An element \( s \in C \) is called an exit state if \( s \downarrow \) or there exists an exit transition from \( s \).

**Example 4.3.** Consider the automaton associated with the \( \text{BPA}^*_{0,1}(A) \) expression \( 1 \cdot (a \cdot (a + 1))^* \cdot b \) (see Figure 2). It has a strongly connected component with two exit states, both with a single exit transition \((d, 1)\).

Non-trivial strongly connected components in \( \text{BPA}^*_{0,1}(A) \) arise from executing the argument of a Kleene star. An exit state of a strongly connected component in \( \text{BPA}^*_{0,1}(A) \) is then a state with the termination option. Due to the presence of \( 0 \) in \( \text{BPA}^*_{0,1}(A) \) this is, however, not the only type of exit state in \( \text{BPA}^*_{0,1}(A) \) strongly connected components.

**Example 4.4.** Consider the automaton associated with the \( \text{BPA}^*_{0,1}(A) \) expression \( 1 \cdot (a \cdot ((b \cdot 0) + 1))^* \cdot c \) (see Figure 3). The strongly connected component contains two
exit states and two (distinct) exit transitions. One of these exit transitions leads to a deadlocked state.

\[
\begin{array}{c}
1 \cdot (a \cdot ((b \cdot 0) + 1))^* \cdot c \\
\downarrow a \\
1 \\
\end{array}
\quad
\begin{array}{c}
((b \cdot 0) + 1) \cdot (a \cdot ((b \cdot 0) + 1))^* \cdot c \\
\downarrow c \\
0 \\
\end{array}
\quad
\begin{array}{c}
0 \cdot (a \cdot ((b \cdot 0) + 1))^* \cdot c \\
\downarrow b \\
1 \\
\end{array}
\]

Fig. 3. A strongly connected component with an unnormed exit transition.

The preceding example illustrates that the special property of strongly connected components in \( \text{BPA}^*_{0,1}(A) \) that we are after, should exclude from consideration any exit transition arising from an occurrence of 0. This is achieved in the following definition.

**Definition 4.5.** Let \( C \) be a strongly connected component and let \( s \in C \). An exit transition \((a, s')\) from \( s \) is **normed** if \( s' \) is normed. We denote by \( ET_n(s) \) the set of normed exit transitions from \( s \).

An exit state \( s \in C \) is **alive** if \( s \downarrow \) or there exists a normed exit transition from \( s \).

Our goal is to prove that any two alive exit states in a strongly connected component \( C \) in \( \text{BPA}^*_{0,1}(A) \) have the same normed exit transitions. We proceed by first characterising the set of exit transitions of a state in \( C \), using its inductive description provided by Corollary 3.11: Lemma 4.7 will deal with the case that \( C \) is a basic non-trivial strongly connected component, and Lemma 4.9 will deal with the case that \( C = C' \cdot q \) for some non-trivial strongly connected component \( C' \) in \( \text{BPA}^*_{0,1}(A) \) and a \( \text{BPA}^*_{0,1}(A) \) expression \( q \).

The following three lemmas are valid not only for \( \text{BPA}^*_{0,1}(A) \), but also for \( \text{PA}^*_{0,1}(A) \) and \( \text{ACP}^*_{0,1}(\gamma) \); in fact, we will reuse them in subsequent sections.

**Lemma 4.6.** Let \( C = C' \cdot q^* \) be a basic strongly connected component. Then \( q \rightarrow^+ p \) for all \( p \in C' \).

**Proof.** Let \( p \in C' \). Note that, since \( C' \) is not a strongly component, there exists \( r \in C' \) such that either \( r \nrightarrow^+ p \) or \( p \nrightarrow^+ r \).

First we consider the case that \( r \nrightarrow^+ p \). Then, since \( C \) is a strongly connected component, it holds that \( r \cdot q^* \rightarrow^+ p \cdot q^* \), so, by Lemma 2.2(2), there exist \( r_0, \ldots, r_k \) such that \( r \cdot q^* = r_0 \cdot q^* \rightarrow^\cdots \rightarrow r_k \cdot q^* = p \cdot q^* \). From \( r \nrightarrow^+ p \) it follows that \( r_\ell \nrightarrow r_{\ell+1} \) for some \( 0 \leq \ell < k \); we let \( \ell \) be the largest such natural number, so that in addition we have \( r_{\ell+1} \rightarrow^+ p \). Then, from \( r_\ell \nrightarrow r_{\ell+1} \) we conclude that the last rule applied in the derivation of \( r_\ell \cdot q^* \rightarrow^\cdots \rightarrow r_{\ell+1} \cdot q^* \) must be rule 8, so \( q^* \rightarrow r_{\ell+1} \cdot q^* \), which by rule 10 implies that \( q \rightarrow r_{\ell+1} \rightarrow^+ p \). Thus, we have now established that \( q \rightarrow r_{\ell+1} \rightarrow^+ p \).

It remains to consider the case that \( r \rightarrow^+ p \) and \( p \nrightarrow^+ r \). Then from \( p \nrightarrow^+ r \) it can be concluded, in a similar manner as above, that \( q \rightarrow^+ r \), and hence \( q \rightarrow^+ p \). \( \square \)
Lemma 4.7. If $C$ is a basic strongly connected component, then $ET_n(p) = \emptyset$ for all $p \in C$.

Proof. Let $p \in C$. To prove that $ET_n(p) = \emptyset$, we suppose that $p$ has a normed exit transition and derive a contradiction. So, let $r$ and $r'$ be process expressions such that $r \not\in C$ and $p \xrightarrow{a} r \xrightarrow{\ast} r' \downarrow$. Since $C$ is a basic strongly connected component, there exist a set of process expressions $C'$ and a process expression $q$ such that $C = C' \cdot q'$. It follows from $p \in C$ that there exists $p' \in C'$ such that $p = p' \cdot q'$, and hence, by Lemma 2.2(2), it follows from $p \xrightarrow{\ast} r'$ that there exists a process expression $s$ such that $r' = s \cdot q'$. Since $r' \downarrow$, according to rule 9, also $s \downarrow$. Hence, since $q \xrightarrow{\ast} p$ by Lemma 4.6, it follows that $r' \xrightarrow{\ast} p$. But then $r' \in C$ and, a fortiori, $r \in C$, contradicting our assumption that $r \not\in C$. We conclude that $p$ does not admit normed exit transitions, and hence $ET_n(p) = \emptyset$. 

Lemma 4.8. Let $C$ be a non-trivial strongly connected component, let $p \in C$, and let $q$ be a process expression such that $C \cdot q$ is a strongly connected component. Then $p \cdot q$ is an alive exit state in $C \cdot q$ iff $p$ is an alive exit state in $C$ and $q$ is normed.

Proof. We prove the implications from left to right and from right to left separately.

($\Rightarrow$) If $p \cdot q$ is an alive exit state in $C \cdot q$, then either $p \cdot q \downarrow$, or there exist $a \in A$ and a normed process expression $r$ such that $p \cdot q \xrightarrow{a} r$ and $r \not\in C \cdot q$.

In the first case it is immediately clear from rule 9 that $p \downarrow$ and $q \downarrow$, so $p$ is an alive exit state in $C$ and $q$ is normed.

In the second case, since $p \cdot q \xrightarrow{a} r$ and $r$ is normed, it follows that $p \cdot q$ is normed, and hence, by Lemma 2.3(1), $q$ is normed. It remains to prove that $p$ is an alive exit state.

To this end, note that from $p \cdot q \xrightarrow{a} r$ it follows that either $p \downarrow$ and $q \xrightarrow{a} r$ or there exists $p'$ such that $p \xrightarrow{a} p'$ and $r = p' \cdot q$. If $p \downarrow$, then $p$ is an alive exit state of $C$ directly by definition. If there exists $p'$ such that $p \xrightarrow{a} p'$ and $r = p' \cdot q$, then it remains to prove that $p' \not\in C$ and $p'$ is normed. Since $p' \in C$ incorrectly implies $r = p' \cdot q \in C \cdot q$, it follows that $p' \not\in C$, and since $r$ is normed, by Lemma 2.3(1) so is $p'$.

($\Leftarrow$) Suppose that $p$ is an alive exit state in $C$ and $q$ is normed. Then there are two cases: either $p \downarrow$, or there exist an $a \in A$ and a normed process expression such that $p \xrightarrow{a} p'$ and $p' \not\in C$. We consider these two cases separately.

Suppose that $p \downarrow$. If also $q \downarrow$, then $p \cdot q \downarrow$, and hence $p \cdot q$ is an alive exit state in $C \cdot q$. If $q \downarrow$, then, since $q$ is normed, there exist $a \in A$ and a normed process expression $q'$ such that $q \xrightarrow{a} q'$. From $p \cdot q \xrightarrow{a} q'$ it follows by Lemma 3.4 that either $\#(p \cdot q) > \#(q')$, or $\#(p \cdot q) = \#(q')$ and there is a $p'$ such that $q' = p' \cdot q$. If $\#(p \cdot q) > \#(q')$, then $(a, q')$ is a normed exit transition from $p \cdot q$, so $p \cdot q$ is an alive exit state in $C \cdot q$.

The other case, that $\#(p \cdot q) = \#(q')$ and there is a $p'$ such that $q' = p' \cdot q$, cannot occur, for $q \xrightarrow{a} p' \cdot q$ implies by Lemma 3.4 and the definition of $\#(.)$ that $q$ is a star expression, which is in contradiction with our assumption that $q \not\in C$.

Suppose there exist $a \in A$ and a normed process expression $p'$ such that $p \xrightarrow{a} p'$ and $p' \not\in C$. Then $p \cdot q \xrightarrow{a} p' \cdot q$, and since $p' \not\in C$ it follows that $p' \cdot q \not\in C \cdot q$. We conclude
that \((a,p' \cdot q)\) is an exit transition of \(p \cdot q\), which, by Lemma 2.3(1), is normed since \(p'\) and \(q\) are both normed.

For a characterisation of the set of normed exit transitions of a sequential composition, it is convenient to have the following notation: if \(E\) is a set of exit transitions and \(p\) is an expression, then \(E \cdot p\) is defined by

\[
E \cdot p = \{(a,q \cdot p) \mid (a,q) \in E\}.
\]

**Lemma 4.9.** Let \(C\) be a non-trivial strongly connected component, let \(p \in C\), and let \(q\) be a normed process expression such that \(C \cdot q\) is a strongly connected component. Then

\[
ET_n(p \cdot q) = \begin{cases} ET_n(p) \cdot q & \text{if } p_n^\|^\prime; \\
ET_n(p) \cdot q \cup \{(a,r) \mid r \notin C \cdot q \land r \text{ is normed } \land \overset{a}{\rightarrow} r\} & \text{if } p_n. 
\end{cases}
\]

**Proof.** We distinguish cases according to whether \(p_n\) or \(p_n^\|^\prime;\):

1. Suppose that \(p_n^\|^\prime;\).
   To see that \(ET_n(p \cdot q) \subseteq ET_n(p) \cdot q\), consider an exit transition \((a,r) \in ET_n(p \cdot q)\). Then \(r\) is a normed process expression such that \(p \cdot q \overset{a}{\rightarrow} r\) and \(r \notin C \cdot q\). Since \(p_n^\|^\prime;\), it follows that there exists \(p'\) such that \(p \overset{a}{\rightarrow} p'\) and \(r = p' \cdot q\). From \(r \notin C \cdot q\), it follows that \(p' \notin C\). Moreover, since \(r\) is normed, by Lemma 2.3(1) \(p'\) is normed too. Thereby, we have now established that \((a,p') \in ET_n(p)\), and hence \((a,r) \in ET_n(p \cdot q)\).
   To see that \(ET_n(p) \cdot q \subseteq ET_n(p \cdot q)\), consider an exit transition \((a,p') \in ET_n(p)\). Then \(p'\) is a normed process expression such that \(p \overset{a}{\rightarrow} p'\) and \(p' \notin C\). Now, since both \(p'\) and \(q\) are normed, by Lemma 2.3(1), \(p' \cdot q\) is normed. Furthermore, \(p \cdot q \overset{a}{\rightarrow} p' \cdot q\), and from \(p' \cdot q \notin C\) it follows that \(p' \cdot q \notin C \cdot q\). Hence, \((a,p' \cdot q) \in ET_n(p \cdot q)\).

2. Suppose that \(p_n\).
   To see that \(ET_n(p \cdot q) \subseteq ET_n(p) \cdot q \cup \{(a,r) \mid r \notin C \cdot q \land r \text{ is normed } \land \overset{a}{\rightarrow} r\}\), consider an exit transition \((a,r) \in ET_n(p \cdot q)\). Then \(r\) is a normed process expression such that \(p \cdot q \overset{a}{\rightarrow} r\) or \(r \notin C \cdot q\). From \(p \cdot q \overset{a}{\rightarrow} r\) and \(p_n\), it follows that either \(q \overset{a}{\rightarrow} r\) or there exists \(p'\) such that \(p \overset{a}{\rightarrow} p'\) and \(r = p' \cdot q\). In the first case it follows that \((a,r) \in \{(a,r) \mid r \notin C \cdot q \land r \text{ is normed } \land \overset{a}{\rightarrow} r\}\). In the second case, note that, since \(r\) is normed, by Lemma 2.3(1) so is \(p'\). Furthermore, \(p' \notin C\), for otherwise \(r = p' \cdot q \in C \cdot q\) contradicting \((a,r) \in ET_n(p \cdot q)\). Hence \((a,p') \in ET_n(p)\).
   To see that \(ET_n(p) \cdot q \subseteq ET_n(p \cdot q)\), consider an exit transition \((a,p') \in ET_n(p)\). Then \(p'\) is a normed process expression such that \(p \overset{a}{\rightarrow} p'\) and \(p' \notin C\). From \(p \overset{a}{\rightarrow} p'\) it follows that \(p \cdot q \overset{a}{\rightarrow} p' \cdot q\), and from \(p' \notin C\) it follows that \(p' \cdot q \notin C \cdot q\). Furthermore, since \(p'\) and \(q\) are both normed, by Lemma 2.3(1) so is \(p' \cdot q\). Hence \((a,p' \cdot q) \in ET_n(p \cdot q)\).
   That \(\{(a,r) \mid r \notin C \cdot q \land r \text{ is normed } \land \overset{a}{\rightarrow} r\} \subseteq ET_n(p \cdot q)\) is immediate.

**Proposition 4.10.** Let \(C\) be a non-trivial strongly connected component in \(\text{BPA}_n^\star(\mathcal{A})\). If \(p_1\) and \(p_2\) are alive exit states in \(C\), then \(ET_n(p_1) = ET_n(p_2)\).

**Proof.** Suppose that \(p_1\) and \(p_2\) are alive exit states; we prove by induction on the
Regular Expressions with Parallel Composition

structure of non-trivial strongly connected components in BPA*$^\star_1$(A) as given by Corollary 3.11 that ET$_n$(p$_1$) = ET$_n$(p$_2$), and p$_1$$\perp$ iff p$_2$$\perp$.

If C is basic, then by Lemma 4.7 ET$_n$(p$_1$) = ∅ = ET$_n$(p$_2$), and, since p$_1$ and p$_2$ are alive exit states, it also follows from this that both p$_1$$\perp$ and p$_2$$\perp$.

Suppose that C = C’ ∪ q, with C’ a non-trivial strongly connected component, and let p’$_1$, p’$_2$ ∈ C’ be such that p$_1$ = p’$_1$ · q and p$_2$ = p’$_2$ · q. Since p$_1$ and p$_2$ are alive exit states, by Lemma 4.8 so are p’$_1$ and p’$_2$, furthermore, q is normed. Hence, by the induction hypothesis, ET$_n$(p’$_1$) = ET$_n$(p’$_2$) and p’$_1$$\perp$ iff p’$_2$$\perp$. From the latter it immediately follows that p$_1$$\perp$ iff p$_2$$\perp$. We now apply Lemma 4.9: if, on the one hand, p$_1$$\perp$ and p$_2$$\perp$, then

\[
ET_n(p_1) = ET_n(p'_1) \cdot q \cup \{(a, r) \mid r \not\in C \land r \text{ is normed } \land q \xrightarrow{a} r\}
\]

\[
= ET_n(p'_2) \cdot q \cup \{(a, r) \mid r \not\in C \land r \text{ is normed } \land q \xrightarrow{a} r\}
\]

\[
= ET_n(p_2) ,
\]

and if, on the other hand, p$_1$$\not\perp$ and p$_2$$\not\perp$, then

\[
ET_n(p_1) = ET_n(p'_1) \cdot q = ET_n(p'_2) \cdot q = ET_n(p_2) .
\]

\[\square\]

**Theorem 4.11.** BPA*$^\star_1$(A) is less expressive than PA*$^\star_1$(A).

**Proof.** According to Definition 2.5 we should prove that every state in BPA*$^\star_1$(A) is bisimilar to a state in PA*$^\star_1$(A) and that there exists a state in PA*$^\star_1$(A) for which there is no bisimilar state in BPA*$^\star_1$(A).

That every state in BPA*$^\star_1$(A) is bisimilar to a state in PA*$^\star_1$(A) is immediately clear.

To prove that there exists a state in PA*$^\star_1$(A) for which there is no bisimilar state in BPA*$^\star_1$(A), consider the PA*$^\star_1$(A) expression 1 · (a · b)$^\star$ || c. Let us use the following abbreviations:

\[
p_0 = 1 \cdot (a \cdot b)^\star || c ,
\]

\[
p_1 = b \cdot (a \cdot b)^\star || c ,
\]

\[
p_2 = 1 \cdot (a \cdot b)^\star || 1 ,
\]

\[
p_3 = b \cdot (a \cdot b)^\star || 1 ;
\]

the automaton associated with this PA*$^\star_1$(A) expression, with the states labelled with the above abbreviations, is shown in Figure 4.

![Fig. 4. A PA*$^\star_1$(A)-expressible automaton that is not expressible in BPA*$^\star_1$(A).](image-url)
To establish that there is no BPA$^{\gamma}_{0,1}(A)$ expression bisimilar to $1 \cdot (a \cdot b)^{\ast} \parallel C$, we assume that $p$ is a BPA$^{\gamma}_{0,1}(A)$ expression bisimilar to $1 \cdot (a \cdot b)^{\ast} \parallel C$ and derive a contradiction. Note that the set $C = \{p_0, p_1\}$ is a non-trivial strongly connected component in PA$^{\gamma}_{0,1}(A)$ and $p_0 \not\equiv p$. Hence, by Lemma 3.2, there is a strongly connected component $C'$ in BPA$^{\gamma}_{0,1}(A)$ reachable from $p$ satisfying the condition that there exist $p'_0, p'_1 \in C'$ such that $p_0 \equiv p'_0$ and $p_1 \equiv p'_1$. From $p_0 \equiv p'_0$ and $p_0 \xrightarrow{a} p_2$ it follows that there exists a BPA$^{\gamma}_{0,1}(A)$ expression $p'_2$ such that $p'_0 \xrightarrow{a} p'_2$ and $p_2 \equiv p'_2$. Similarly, from $p_1 \equiv p'_1$ and $p_1 \xrightarrow{b} p_3$, it follows that there exists a BPA$^{\gamma}_{0,1}(A)$ expression $p'_3$ such that $p'_1 \xrightarrow{b} p'_3$ and $p_3 \equiv p'_3$.

It is easy to see that $p'_2 \not\equiv C'$, for $p'_2 \in C'$ would imply the existence of a transition sequence $p'_2 \xrightarrow{a} p'_0 \xrightarrow{a} p'_2$ that clearly cannot be simulated by $p_2$. For similar reasons, $p'_3 \not\equiv C'$. So $(b, p'_2)$ and $(c, p'_3)$ are exit transitions. From $p_2 \equiv p'_2$ and $p_2 \xrightarrow{a}$ it follows that $p_2 \xrightarrow{a}$, so $(b, p'_2)$ is normed. From $p_3 \equiv p'_3$ and $p_1 \xrightarrow{b} p_2$ it follows that there exists $p'_2$ such that $p'_1 \xrightarrow{b} p'_2$ and $p_2 \equiv p'_2$, and thereby $p'_2 \xrightarrow{a}$, and hence $(c, p'_3)$ is normed.

We conclude that both $p'_0$ and $p'_1$ are alive exit states. By Proposition 4.10 $p'_0$ and $p'_1$ have the same normed exit transitions, so, in particular, $p'_0 \xrightarrow{a} p'_3$. Since $p_0 \equiv p'_0$, it follows that $p_2 \equiv p'_1 \equiv p_3$, and hence $p_2 \equiv p_3$, which is clearly not the case. Thus, we have now arrived at a contradiction. 

\[ \square \]

5. Relative Expressiveness of PA$^{\gamma}_{0,1}(A)$ and ACP$^{\gamma}_{0,1}(A, \gamma)$

Bergstra et al.'s (2001) proof that PA$^{\gamma}_{\ast}(A)$ is less expressive than ACP$^{\gamma}_{\ast}(A, \gamma)$ uses the same expression as the one showing that BPA$^{\gamma}_{\ast}(A)$ is less expressive than PA$^{\gamma}_{\ast}(A)$, but it presupposes that $\gamma(c,d) = e$. It is claimed that the associated automaton fails the following general property of cycles in PA$^{\gamma}_{\ast}(A)$:

If $C$ is a cycle reachable from a PA$^{\gamma}_{\ast}(A)$ process term and there is a state in $C$ with a transition to a terminating state, then all other states in $C$ have only successors in $C$.

The claim, however, is incorrect, as illustrated by the following example. (To avoid having to introduce the syntax and operational semantics of PA$^{\ast}_{\gamma}(A)$ formally, we present the example in the syntax of PA$^{\gamma}_{0,1}(A)$. To translate it into the syntax of PA$^{\ast}_{\gamma}(A)$, the occurrence of $1 \cdot$ should be removed, and $\ast$ should be replaced by (the binary version of) $\ast$; we refer to (Bergstra et al. 2001) for the operational semantics of PA$^{\ast}_{\gamma}(A)$.)

**Example 5.1.** Consider the PA$^{\gamma}_{0,1}(A)$ expression $(a \cdot (b + b \cdot b)) \ast \cdot d$ (see Figure 5 for the complete associated automaton), from which the cycle

\[ C = \{1 \cdot (a \cdot (b + b \cdot b)) \ast \cdot d, (b + b \cdot b) \cdot (a \cdot (b + b \cdot b)) \ast \cdot d\} \]

is reachable. Clearly, the first expression in $C$ can perform a $d$-transition to $1$. Then, according to the property above, every other expression only has transitions to expressions in $C$. However,

\[(b + b \cdot b) \cdot (a \cdot (b + b \cdot b)) \ast \cdot d \xrightarrow{b} b \cdot (a \cdot (b + b \cdot b)) \ast \cdot d \not\in C.\]

If we replace, in the property above, the notion of cycle by the notion of strongly
connected component, then the resulting property does hold for \(\text{PA}_0(A)\), but it still fails for \(\text{PA}_{0.1}(A)\).

**Example 5.2.** Consider the \(\text{PA}_{0.1}(A)\) expression \((a \cdot b)^* \parallel c\) (see Figure 6 for the associated automaton); it gives rise to the following non-trivial strongly connected component:

\[
\{1 \cdot (a \cdot b)^* \parallel c, b \cdot (a \cdot b)^* \parallel c\}.
\]

The expression \(1 \cdot (a \cdot b)^* \parallel c\) can do a \(c\)-transition to \(1 \cdot (a \cdot b)^* \parallel 1\), for which the termination predicate holds, but at the same time \(b \cdot (a \cdot b)^* \parallel c\) has an exit transition \((c, b \cdot (a \cdot b)^* \parallel 1)\).

![Fig. 6. A \(\text{PA}_{0.1}(A)\)-expressible automaton with a strongly connected component and multiple (different) exit transitions.](image)

In this section we shall establish that \(\text{PA}_{0.1}(A)\) is less expressive than \(\text{ACP}_{0.1}^{\vdash \theta}(A, \gamma)\). We use the syntactic characterisation of strongly connected components in \(\text{PA}_{0.1}(A)\) as given by Corollary 3.10 to conclude that a weakened version of the aforementioned property for strongly connected components holds in \(\text{PA}_{0.1}(A)\). Then, we present an \(\text{ACP}_{0.1}^{\vdash \theta}(A, \gamma)\) expression that does not satisfy it.

In Section 4 we deduced, from our syntactic characterisation of strongly connected components in \(\text{BPA}_{0.1}(A)\), the property that all alive exit states of a strongly connected component have the same sets of normed exit transitions. This property may fail for strongly connected components in \(\text{PA}_{0.1}(A)\): the automaton in Figure 4 is \(\text{PA}_{0.1}(A)\)-expressible, but the alive exit states \(p_0\) and \(p_1\) of the strongly connected component \(\{p_0, p_1\}\) have different normed exit transitions. Note, however, that these normed exit transitions both end up in another strongly connected component \(\{p_2, p_3\}\). It turns out that we can relax the requirement on normed exit transitions from strongly connected
components in $\text{BPA}^*_{0,1}(\mathcal{A})$ to get a requirement that holds for strongly connected components in $\text{PA}^*_{0,1}(\mathcal{A})$. The idea is to identify exit transitions if they have the same action and end up in the same strongly connected component.

**Definition 5.3.** Let $\mathcal{T} = (S, \rightarrow, \downarrow)$ be an $\mathcal{A}$-labelled transition system space. We define a binary relation $\sim$ on $\mathcal{A} \times S$ by $(a, s) \sim (a', s')$ iff $a = a'$ and $s$ and $s'$ are in the same strongly connected component in $\mathcal{T}$.

Since the relation of being in the same strongly connected component is an equivalence on states in a transition system space, it is clear that $\sim$ is an equivalence relation on exit transitions. The following lemma, which is valid both in $\text{PA}^*_{0,1}(\mathcal{A})$ and $\text{ACP}^*_{0,1}(\mathcal{A}, \gamma)$, will give some further properties of the relation $\sim$.

**Lemma 5.4.** Let $p$, $q$ and $r$ be process expressions, and let $a$ and $b$ be actions.

1. If $(a, p) \sim (b, q)$, then $(a \cdot p \cdot r) \sim (b \cdot q \cdot r)$.
2. If $(a, p) \sim (b, q)$, then $(a \parallel r) \sim (b \parallel q)$.
3. If $(a, p) \sim (b, q)$, then $(a \parallel p \parallel q) \sim (b \parallel r \parallel q)$.

**Proof.** Suppose that $(a, p) \sim (b, q)$. Then $a = b$, and $p$ and $q$ are in the same strongly connected component of $\text{PA}^*_{0,1}(\mathcal{A})$. So $p \rightarrow^* q \rightarrow^* p$, and hence $p \cdot r \rightarrow^* q \cdot r \rightarrow^* p \cdot r$, $p \parallel r \rightarrow^* q \parallel r \rightarrow^* p \parallel r$, and $r \parallel p \rightarrow^* r \parallel q \rightarrow^* r \parallel p$. From this it follows that $p \cdot r$ and $q \cdot r$, $p \parallel r$ and $q \parallel r$, and $r \parallel p$ and $r \parallel q$, are in the same strongly connected component, and hence $(a, p \cdot r) \sim (b, q \cdot r)$, $(a, p \parallel r) \sim (b, q \parallel r)$, and $(a \parallel p \parallel r) \sim (b, r \parallel q)$.

The following notation will be convenient in the sequel: If $e = (a, p)$ is an exit transition, then $e \parallel q = (a, p \parallel q)$ and $q \parallel e = (a, q \parallel p)$. If $E$ is a set of exit transitions $E$ and $p$ is a $\text{PA}^*_{0,1}(\mathcal{A})$ expression, then $E \parallel p$ and $p \parallel E$ are defined by

$$E \parallel p = \{ e \parallel p \mid e \in E \} \text{ , and } \quad p \parallel E = \{ p \parallel e \mid e \in E \} .$$

For a succinct formulation of the property that will allow us to property that $\text{PA}^*_{0,1}(\mathcal{A})$ is less expressive than $\text{ACP}^*_{0,1}(\mathcal{A}, \gamma)$, it is convenient to extend the definition of normedness to strongly connected components.

**Definition 5.5.** A strongly connected component $C$ is normed if all states in $C$ are normed.

The following lemma explains how extending the definition of normedness to strongly connected components is conducive to succinct formulation: to ensure that a strongly connected component has alive exit states, it suffices to require that it is normed.

**Lemma 5.6.** Let $C$ be a strongly connected component. Then $C$ is normed iff it has alive exit states.

**Proof.** Note that if $C$ contains a normed state, then $C$ is normed. Hence, since an alive exit state is clearly normed, the implication from right to left is immediate. It remains to establish the implication from left to right. To this end, let $s \in C$. Since $C$ is normed, there exists a process expression $s'$ such that $s \rightarrow^* s'$ and $s' \downarrow$. On the one hand, if $s' \in C$, then...
then $s'$ is an alive exit state. On the other hand, if $s' \notin C$, then there exist states $s_1 \in C$ and $s_2 \notin C$ and an action $a$ such that $s \xrightarrow{a} s_1 \xrightarrow{a} s_2 \xrightarrow{a} s'$. Then, clearly, $(a, s_2)$ is a normed exit transition from $s_1$, so $s_1$ is an alive exit state.

We proceed, in the following lemma, to characterise the set of normed exit transitions in a normed strongly connected component of the form $C_1 \parallel C_2$ in $\mathcal{PA}_{0,1}(A)$ in terms of the normed exit transitions in the constituent normed strongly connected components $C_1$ and $C_2$.

**Lemma 5.7.** Let $C_1$ and $C_2$ be normed strongly connected components in $\mathcal{PA}_{0,1}(A)$. Then $C_1 \parallel C_2$ is a normed strongly connected component, and for all $p \in C_1$ and $q \in C_2$,

$$ET_n(p \parallel q) = (ET_n(p) \parallel q) \cup (p \parallel ET_n(q)) \ .$$

**Proof.** Suppose that $C_1$ and $C_2$ are normed strongly connected components. Then, by Corollary 3.9, $C_1 \parallel C_2$ is a strongly connected component too, which, by Lemma 2.3(2), is normed. It remains to prove that for all $p \in C_1$ and $q \in C_2$

$$ET_n(p \parallel q) = (ET_n(p) \parallel q) \cup (p \parallel ET_n(q)) \ .$$

To prove that $ET_n(p \parallel q) \subseteq (ET_n(p) \parallel q) \cup (p \parallel ET_n(q))$, consider an arbitrary $(a, r) \in ET_n(p \parallel q)$. Then $r$ is a normed $\mathcal{PA}_{0,1}(A)$ expression such that $p \parallel q \xrightarrow{a} r$ and $r \notin C_1 \parallel C_2$. From the operational rules for $\mathcal{PA}_{0,1}(A)$ with $\parallel$ in the conclusion it follows that we can distinguish two cases: either there exists $p'$ such that $r = p' \parallel q$ and $p \xrightarrow{a} p'$, or there exists $q'$ such that $r = p \parallel q'$ and $q \xrightarrow{a} q'$. The proofs for these cases are entirely analogous; we only present details for the first case. Since $q \in C_2$, $p' \parallel q \notin C_1 \parallel C_2$ implies that $p' \notin C_1$, and, since $r$ is normed and $r = p' \parallel q$, by Lemma 2.3(1) $p'$ is normed too. It follows that $(a, p') \in ET_n(p)$, and hence $(a, r) \in ET_n(p \parallel q)$.

To prove that $(ET_n(p) \parallel q) \subseteq ET_n(p \parallel q)$ consider an arbitrary $(a, r) \in ET_n(p \parallel q)$. Then there exists a $\mathcal{PA}_{0,1}(A)$ expression $p'$ such that $(a, p') \in ET_n(p)$ and $r = p' \parallel q$. From $(a, p') \subseteq ET_n(p)$ it follows that $p'$ is a normed $\mathcal{PA}_{0,1}(A)$ expression such that $p \xrightarrow{a} p'$ and $p' \notin C_1$. From the latter, it follows that $p' \xrightarrow{a}^* p$ and hence, by Lemma 2.2(3), $p' \parallel q \xrightarrow{a}^* p \parallel q$, so $p' \parallel q \notin C_1 \parallel C_2$. Further note that, by our assumption that $C_2$ is normed, $q$ is normed, so, by Lemma 2.3(2), $p' \parallel q$ is normed. We conclude that $(a, p' \parallel q) \subseteq ET_n(p \parallel q)$.

The proof that $(p \parallel ET_n(q)) \subseteq ET_n(p \parallel q)$ is completely analogous to the proof that $(ET_n(p) \parallel q) \subseteq ET_n(p \parallel q)$, so the proof of the lemma is now complete.

To formulate the special property of strongly connected components in $\mathcal{PA}_{0,1}(A)$ that will allow us to prove that some $\mathcal{ACP}_{0,1}^\mathcal{A}(A, \gamma)$ expressions do not have a counterpart in $\mathcal{PA}_{0,1}(A)$, we need the following notion of maximal alive exit state.

**Definition 5.8.** Let $T = (S, \rightarrow, \downarrow)$ be an $\mathcal{A}$-labelled transition system space, let $\sim$ be the equivalence relation on $A \times S$ associated with $T$ according to Definition 5.3, let $C$ be a strongly connected component in $T$, and let $s \in C$ be an alive exit state. We say that $s$ is maximal (modulo $\sim$) if for all alive exit states $s' \in C$ and for all $e' \in ET_n(s')$ there exists an exit transition $e \in ET_n(s)$ such that $e \sim e'$. 
We are now at the position to establish the property with which we shall prove that \( PA^*_{0,1}(A) \) is less expressive than \( \text{ACP}^*_{0,1}(A, \gamma) \).

**Proposition 5.9.** Every normed strongly connected component in \( PA^*_{0,1}(A) \) has a maximal alive exit state.

*Proof.* Let \( C \) be a normed strongly connected component in \( PA^*_{0,1}(A) \). If \( C \) is trivial, then \( C \) is a singleton, say \( C = \{p_m\} \), and, since \( C \) is normed, by Lemma 5.6 \( p_m \) is an alive exit state that is, vacuously, maximal. So, for the remainder of the proof we may assume that \( C \) is non-trivial. We proceed to prove with induction on the structure of \( C \), as given by Corollary 3.10, that \( C \) has a maximal alive exit state \( p_m \) such that, in addition, \( p_m \downarrow \) if \( p \downarrow \) for some \( p \in C \). We distinguish three cases:

1. If \( C \) is basic, then, by Lemma 4.7, \( ET_n(p) = \emptyset \) for all \( p \in C \). Since \( C \) is normed, by Lemma 5.6 it contains an alive exit state, say \( p_m \), which is then vacuously maximal and satisfies \( p_m \downarrow \).

2. Suppose that \( C = C' \cdot q \) with \( C' \) a non-trivial strongly connected component and \( q \) a \( PA^*_{0,1}(A) \) expression. Since \( C \) is normed, by Lemma 5.6 it contains an alive exit state, say \( p_m \), and \( q \) is normed. Hence, by the induction hypothesis, \( C' \) has a maximal alive exit state \( p_m \in C' \) such that \( p_m \downarrow \) if \( p \downarrow \) for some \( p \in C' \). By Lemma 4.8 \( p_m \cdot q \) is an alive exit state in \( C \). If \( p \cdot q \downarrow \) for some \( p \in C' \), then \( p \downarrow \) and \( q \downarrow \), so \( p_m \downarrow \) and hence \( p_m \downarrow \cdot q \downarrow \).

For this case it therefore remains to prove that \( p_m \cdot q \) is maximal. To this end, consider an alive exit state \( p \cdot q \in C \) and let \( (a, r) \) be a normed exit transition from \( p \cdot q \). Then by Lemma 4.9 either there exist \( p' \) such that \( r = p' \cdot q \) and \( (a, p') \) is a normed exit transition from \( p \), or \( q \downarrow \) and \( (a, r) \) is a normed exit transition from \( p \cdot q \). In the first case, since \( p_m \) is maximal, there exists a \( PA^*_{0,1}(A) \) expression \( p_m' \) such that \( (a, p_m') \) is a normed exit transition from \( p_m \) and \( (a, p_m') \sim (a, p') \); it follows by Lemma 4.9 that \( (a, p_m' \cdot q) \) is a normed exit transition from \( p_m \cdot q \), and by Lemma 5.4 \( (a, p_m' \cdot q) \sim (a, r) \). In the second case, since \( q \downarrow \) implies \( p_m \downarrow \cdot (a, r) \) is a normed exit transition from \( p_m \cdot q \).

3. Suppose that \( C = C_1 \parallel C_2 \) with \( C_1 \) and \( C_2 \) strongly connected components. Since \( C \) is normed, by Lemma 2.3(2) both \( C_1 \) and \( C_2 \) are normed. Hence, by the induction hypothesis \( C_1 \) has a maximal alive exit state \( p_m \) and \( C_2 \) has a maximal alive exit state \( q_m \). Moreover, also by the induction hypothesis, \( p_m \downarrow \) if \( p \downarrow \) for some \( p \in C_1 \) and \( q_m \downarrow \) if \( q \downarrow \) for some \( q \in C_2 \). We argue that \( p_m \parallel q_m \) is a maximal alive exit state in \( C \), and that whenever \( p \parallel q \) for some \( p \parallel q \in C \), then also \( p_m \parallel q_m \).

Note that if \( p \parallel q \downarrow \) for some \( p \parallel q \in C \), then, according to operational rule 14, \( p \downarrow \) and \( q \downarrow \), so \( p_m \downarrow \) and \( q_m \downarrow \), and hence \( p_m \parallel q_m \downarrow \). To see that \( p_m \parallel q_m \) is maximal, suppose that \( e \in ET_n(p \parallel q) \) for some \( p \parallel q \in C \). Then by Lemma 5.7 there are two cases: either there exists \( e' \in ET_n(p) \) such that \( e = e' \parallel q \), or there exists \( e' \in ET_n(q) \) such that \( e = p \parallel e' \). In the first case, if \( e' \in ET_n(p) \), then by the induction hypothesis there exists \( e'' \in ET_n(p_m) \) such that \( e'' \sim e' \). By Lemma 5.7, \( e'' \parallel q_m \in ET_n(p_m \parallel q_m) \) and since \( q_m \) and \( q_m \) are in the same strongly connected component \( C_2 \), it is clear that \( e'' \parallel q_m \sim e \). In the second case, if
We can now prove the main result of this section.

**Theorem 5.10.** \( \text{PA}_{0,1}^\ast(A) \) is less expressive than \( \bigcup \gamma \text{ACP}_{0,1}^\ast\partial(A, \gamma) \).

*Proof.* According to Definition 2.5 we should prove that every state in \( \text{PA}_{0,1}^\ast(A) \) is bisimilar to a state in \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) and that there exists a state in \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) for which there is no bisimilar state in \( \text{PA}_{0,1}^\ast(A) \).

That every state in \( \text{PA}_{0,1}^\ast(A) \) is bisimilar to a state in \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) is immediate since \( \text{PA}_{0,1}^\ast(A) \) is included in \( \bigcup \gamma \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) as \( \text{ACP}_{0,1}^\ast\partial(A, \emptyset) \).

To prove that there exists a state in \( \bigcup \gamma \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) for which there is no bisimilar state in \( \text{PA}_{0,1}^\ast(A) \), consider the \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \) expression \( \{ a \cdot b \}^* \cdot d \parallel c \) with \( \gamma \) satisfying \( \gamma(b, c) = \gamma(c, b) = e \) and \( \gamma \) undefined everywhere else. Let us use the following abbreviations:

\[
\begin{align*}
p_0 & = 1 \cdot (a \cdot b)^* \cdot d \parallel c , \\
p_1 & = 1 \cdot b \cdot (a \cdot b)^* \cdot d \parallel c , \\
p_2 & = 1 \cdot (a \cdot b)^* \cdot d \parallel 1 , \\
p_3 & = 1 \cdot b \cdot (a \cdot b)^* \cdot d \parallel 1 , \\
p_4 & = 1 \parallel c , \text{ and} \\
p_5 & = 1 \parallel 1 ;
\end{align*}
\]

the automaton associated with \( p_0 \), with the states labelled with the above abbreviations, is shown in Figure 7.

![Fig. 7. An \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \)-expressible automaton that is not expressible in \( \text{PA}_{0,1}^\ast(A) \).](image)

To establish that there is no \( \text{PA}_{0,1}^\ast(A) \) expression bisimilar to \( p_0 \), we assume that \( p \) is such a \( \text{PA}_{0,1}^\ast(A) \) expression and derive a contradiction. Note that the set \( C = \{ p_0, p_1 \} \) is a strongly connected component in \( \text{ACP}_{0,1}^\ast\partial(A, \gamma) \). Hence, since \( p_0 \not\simeq p_1 \), by Lemma 3.2 there is a strongly connected component \( C' \) in \( \text{PA}_{0,1}^\ast(A) \) reachable from \( p \) satisfying the condition that there exist \( p_0', p_1' \in C' \) such that \( p_0 \not\simeq p_0' \) and \( p_1 \not\simeq p_1' \). Clearly, \( C' \) is normed, so by Proposition 5.9 it has a maximal alive exit state. From \( p_0 \not\simeq p_0' \) it follows that there exists \( p_0'' \not\in C' \) such that \( p_0 \not\overset{\alpha}{\rightarrow} p_0'' \) and \( p_1 \not\overset{\gamma}{\rightarrow} p_0'' \). From \( p_1 \not\simeq p_1' \) it follows that there exists \( p_1'' \not\in C' \) such that \( p_1' \not\overset{\alpha}{\rightarrow} p_1'' \) and \( p_2 \not\simeq p_1'' \). So, on the one hand, both \( p_0' \) and
are alive exit states. On the other hand, \( p'_0 \) does not have a normed exit transition labelled with \( c \) and \( p_1 \) does not have a normed exit transition labelled with \( d \). It is, moreover, easy to see that every state \( p' \in C' \) is bisimilar to either \( p'_0 \) or \( p'_1 \). We conclude that \( C' \) does not have a maximal alive exit state, and thus arrive at a contradiction. We conclude that \( p_0 \) is not \( \text{PA}^{\sim 0,1}_0(A) \)-expressible.

6. Relative Expressiveness of \( \text{ACP}^{\sim \gamma,0}_0(A, \gamma) \) and \( \text{ACP}^{\sim \gamma}_1(A, \gamma) \)

In the next section we shall prove that every finite automaton is expressible in \( \text{ACP}^{\sim \gamma}_1(A, \gamma) \). The purpose of this section is to prove that encapsulation is actually an essential ingredient in this result: we shall prove that \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \) is less expressive than \( \text{ACP}^{\sim \gamma}_1(A, \gamma) \), which extends \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \) with encapsulation. The proof proceeds by an adaptation of the proof of the previous section. It suffices to relax the property stating the existence of a maximal alive exit state, which, as we have seen in Figure 7, fails for strongly connected components in \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \). In \( \text{ACP}^{\sim \gamma}_1(A, \gamma) \) there does not necessarily exist an alive exit state that, up to \( \sim \), has all the exit transitions of all other alive exit states. But there does exist a special alive exit state that, up to \( \sim \), always shares at least one exit transition with every other alive exit state.

Operational rule 15 gives rise to additional transitions from parallel compositions. As a consequence, the characterisation of the set of normed exit transitions in a normed strongly connected component of the form \( C_1 \parallel C_2 \) in Lemma 5.7 does not hold for normed strongly connected components in \( \text{ACP}^{\sim \gamma}_1(A, \gamma) \). But we do have the following weaker property.

**Lemma 6.1.** Let \( C_1 \) and \( C_2 \) be normed strongly connected components in \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \). Then \( C_1 \parallel C_2 \) is a normed strongly connected component, and for all \( p \in C_1 \) and \( q \in C_2 \)

\[
(ET_n(p) \parallel q) \cup (p \parallel ET_n(q)) \subseteq ET_n(p \parallel q) \quad \text{and} \quad ET_n(p) \cup ET_n(q) = \emptyset \iff ET_n(p \parallel q) = \emptyset.
\]

**Proof.** Suppose that \( C_1 \) and \( C_2 \) are strongly connected components with alive exit states. Then, by Proposition 3.5, \( C_1 \parallel C_2 \) is a strongly connected component too, which, by Lemma 2.3(2), is normed. So it remains to prove that for all \( p \in C_1 \) and \( q \in C_2 \)

\[
(ET_n(p) \parallel q) \subseteq ET_n(p \parallel q) ;
\]

\[
(p \parallel ET_n(q)) \subseteq ET_n(p \parallel q) ; \quad \text{and} \quad ET_n(p) \cup ET_n(q) = \emptyset \iff ET_n(p \parallel q) = \emptyset.
\]

To prove that \( (ET_n(p) \parallel q) \subseteq ET_n(p \parallel q) \) consider an arbitrary \( (a, r) \in ET_n(p \parallel q) \). Then there exists an \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \) expression \( p' \) such that \( (a, p') \in ET_n(p) \) and \( r = p' \parallel q \). From \( (a, p') \in ET_n(p) \) it follows that \( p' \) is a normed \( \text{ACP}^{\sim \gamma}_0(A, \gamma) \) expression such that \( p' \overset{\alpha}{\rightarrow} p' \) and \( p' \notin C_1 \). From the latter, it follows that \( p' \overset{\neg \alpha}{\not\rightarrow} p \) and hence, by Lemma 2.2(3), \( p' \parallel q \overset{\neg \alpha}{\not\rightarrow} p \parallel q \), so \( p' \parallel q \notin C_1 \parallel C_2 \). Note that, since \( C_2 \) is normed, \( q \) is normed, so, by Lemma 2.3(2), \( p' \parallel q \) is normed. We conclude that \( (a, p' \parallel q) \in ET_n(p \parallel q) \).

The proof that \( (p \parallel ET_n(q)) \subseteq ET_n(p \parallel q) \) is completely analogous to the proof that \( (ET_n(p) \parallel q) \subseteq ET_n(p \parallel q) \).
Note that from \((ET_n(p \parallel q) \subseteq ET_n(p \parallel q)\) and \((p \parallel ET_n(q)) \subseteq ET_n(p \parallel q)\) it immediately follows that if \(ET_n(p \parallel q) = \emptyset\), then \(ET_n(p) = \emptyset\) and \(ET_n(q) = \emptyset\). So, it remains to prove that if \(ET_n(p) = \emptyset\) and \(ET_n(q) = \emptyset\), then \(ET_n(p \parallel q) = \emptyset\). We proceed by contraposition and assume \(ET_n(p \parallel q) \neq \emptyset\). Then there is \((a, r) \in ET_n(p \parallel q)\), so \(r\) is a normed \(ACP_{0.1}^\ast(A, \gamma)\) expression such that \(p \parallel q \xrightarrow{a} r\) and \(r \notin C_1 \parallel C_2\). From the operational rules for \(ACP_{0.1}^\ast(A, \gamma)\) with \(\parallel\) in the conclusion it follows that we can distinguish three cases: either there exists \(p'\) such that \(r = p' \parallel q\) and \(p \xrightarrow{a} p'\), or there \(q'\) such that \(r = p \parallel q'\) and \(q \xrightarrow{a} q'\), or there exists \(p'\) and \(q'\) such that \(r = p' \parallel q'\), \(p \xrightarrow{b} p'\) and \(q \xrightarrow{c} q'\), and \((b, c) = a\).

In the first case, since \(q \in C_2\), \(p' \parallel q \notin C_1 \parallel C_2\) implies that \(p' \notin C_1\), and, since \(r\) is normed and \(r = p' \parallel q\), by Lemma 2.3(2) \(p'\) is normed too. It follows that \((a, p') \in ET_n(p)\), and hence \(ET_n(p) \neq \emptyset\).

In the second case, by an analogous argument as in the first case, \((a, q') \in ET_n(q)\), and hence \(ET_n(q) \neq \emptyset\).

Finally, in the third case, as \(p' \parallel q' \notin C_1 \parallel C_2\), either \(p' \notin C_1\) or \(q' \notin C_2\). Without loss of generality, we can assume that \(p' \notin C_1\). Since \(r\) is normed and \(r = p' \parallel q'\), by Lemma 2.3(2) \(p'\) is normed too. It follows that \((a, p') \in ET_n(p)\), and hence \(ET_n(p) \neq \emptyset\).

To formulate the property of strongly connected components in \(ACP_{0.1}^\ast(A, \gamma)\) that will allow us to prove that some \(ACP_{0.1}^\ast(A, \gamma)\) expressions do not have a counterpart in \(ACP_{0.1}^\ast(A, \gamma)\), we use the following notion.

**Definition 6.2.** Let \(T = (S, \xrightarrow{}, \downarrow)\) be an \(A\)-labelled transition system space, let \(\sim\) be the equivalence relation on \(A \times S\) associated with \(T\) according to Definition 5.3, let \(C\) be a strongly connected component in \(T\), and let \(s \in C\) be an alive exit state. We say that \(s\) is dominating (modulo \(\sim\)) if for every alive exit state \(s' \in C\) such that \(ET_n(s') \neq \emptyset\) there exist \(e \in ET_n(s)\) and \(e' \in ET_n(s')\) such that \(e \sim e'\).

Note that if an alive exit state is maximal, then it is also dominating.

The following proposition establishes the property with which we shall prove that \(ACP_{0.1}^\ast(A, \gamma)\) is less expressive than \(ACP_{0.1}^\ast(A, \gamma)\).

**Proposition 6.3.** If \(C\) is a normed strongly connected component in \(ACP_{0.1}^\ast(A, \gamma)\), then \(C\) has a dominating alive exit state.

**Proof.** Suppose that \(C\) is a normed strongly connected component in \(ACP_{0.1}^\ast(A, \gamma)\). If \(C\) is trivial, then \(C\) is a singleton, say \(C = \{p_d\}\), and, since \(C\) is normed, by Lemma 5.6 \(p_d\) is an alive exit state that is, vacuously, dominating. So, for the remainder of the proof we may assume that \(C\) is non-trivial. We proceed to prove with induction on the structure of \(C\), as given by Proposition 3.8, that \(C\) has a dominating alive exit state \(p_d\) such that, in addition, \(p_d\downarrow\) if \(p\downarrow\) for some \(p \in C\). We distinguish three cases:

1. If \(C\) is basic, then, by Lemma 4.7, \(ET_n(p) = \emptyset\) for all \(p \in C\). Since \(C\) is normed, by Lemma 5.6 it contains an alive exit state, say \(p_d\), which is then vacuously dominating and satisfies \(p_d\downarrow\).
2 Suppose that $C = C' \cdot q$ with $C'$ a non-trivial strongly connected component and $q$ an $\ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$ expression. Since $C$ is normed, by Lemma 5.6 it contains an alive exit state, say $p' \cdot q$ with $p' \in C'$; then, by Lemma 4.8, $p'$ is an alive exit state in $C'$ and $q$ is normed. Hence, by the induction hypothesis, $C'$ has a dominating alive exit state $p_d \in C'$ such that $p_d \downarrow$ if $p \downarrow$ for some $p \in C'$. By Lemma 4.8, $p_d \cdot q$ is an alive exit state in $C$. If $p \cdot q \downarrow$ for some $p \in C'$, then $p_d \downarrow$ and hence $p_d \cdot q \downarrow$. For this case it therefore remains to prove that $p_d \cdot q$ is dominating. To this end, consider an alive exit state $p \cdot q \in C$ such that $ET_n(p \cdot q) \neq \emptyset$. We distinguish two cases:

On the one hand, if $ET_n(p) = \emptyset$, then, according to Lemma 4.9, $p_d \downarrow$ and

$$ET_n(p \cdot q) = \{(a, r) \mid r \notin C \land r \text{ is normed } \land q \xrightarrow{\gamma} r\}.$$  

Since $ET_n(p \cdot q) \neq \emptyset$, there exists $r$ such that $r \notin C$, $r$ is normed, and $q \xrightarrow{\gamma} r$. Since, by the induction hypothesis, $p_d \downarrow$, it follows that $p_d \cdot q \xrightarrow{\gamma} r$, so $(a, r) \in ET_n(p_d \cdot q)$, and clearly $(a, r) \sim (a, r)$.

On the other hand, if $ET_n(p) \neq \emptyset$, then, by the induction hypothesis, there exist $e \in ET_n(p_d)$ and $e' \in ET_n(p)$ such that $e \sim e'$. By Lemma 4.9, $e \cdot q \in ET_n(p_d \cdot q)$ and $e' \cdot q \in ET_n(p \cdot q)$, and, by Lemma 5.4, $e \cdot q \sim e' \cdot q$.

3 Suppose that $C = C_1 \parallel C_2$ with $C_1$ and $C_2$ strongly connected components. Since $C$ is normed, by Lemma 2.3(2), both $C_1$ and $C_2$ are normed. Hence, by the induction hypothesis, $C_1$ has a dominating alive exit state $p_d$ and $C_2$ has a dominating alive exit state $q_d$. Moreover, also by the induction hypothesis, $p_d \downarrow$ if $p \downarrow$ for some $p \in C_1$, and $q_d \downarrow$ if $q \downarrow$ for some $q \in C_2$. We argue that $p_d \parallel q_d$ is a dominating alive exit state in $C$, and that if $p \parallel q \downarrow$ for some $p \parallel q \in C$, then $p_d \parallel q_d \downarrow$.

Note that if $p \parallel q \downarrow$ for some $p \parallel q \in C$, then $p_d \parallel q_d \downarrow$, and hence $p_d \parallel q_d \downarrow$.

To prove that $p_d \parallel q_d$ is a dominating alive exit state, let $p \parallel q$ be an alive exit state in $C$ such that $ET_n(p \parallel q) \neq \emptyset$. Then, by Lemma 6.1, at least one of $ET_n(p)$ and $ET_n(q)$ is non-empty; without loss of generality, we can assume that $ET_n(p) \neq \emptyset$. Since $p_d$ is a dominating alive exit state in $C_1$, there exist $(a, p'_d) \in ET_n(p_d)$ and $(a, p') \in ET_n(p)$ such that $(a, p'_d) \sim (a, p')$.

Note that, by Lemma 6.1, on the one hand, $(a, p'_d \parallel q_d) \in ET_n(p_d \parallel q_d)$, and, on the other hand, $(a, p' \parallel q) \in ET_n(p \parallel q)$. Moreover, from $(a, p'_d) \sim (a, p')$ it follows that $p'_d$ and $p'$ are in the same strongly connected component, and hence, since also $q_d$ and $q$ are in the same strongly connected component, $p'_d \parallel q_d$ and $p' \parallel q$ are in the same strongly connected component. Therefore, $(a, p'_d \parallel q_d) \sim (a, p' \parallel q)$.

We can now prove the main result of this section.

**Theorem 6.4.** $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$ is less expressive than $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$.

**Proof.** We have to prove that every state in $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$ is bisimilar to a state in $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$ and that there exists a state in $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$ for which there is no bisimilar state in $\bigcup_\gamma \ACP_{0,1}^{\ast\mathbb{N}}(A, \gamma)$.
That every state in $\bigcup_{\gamma} \mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ is bisimilar to a state in $\bigcup_{\gamma} \mathsf{ACP}_{0.1}^{\varnothing}(A, \gamma)$ is immediate.

It remains to prove that there exists a state in $\bigcup_{\gamma} \mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ for which there is no bisimilar state in $\bigcup_{\gamma} \mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$. To this end, we define

$$C = \{\text{enter}_i, \text{leave}_{\alpha,i} \mid 0 \leq i \leq 2, \alpha \in \{a, b, c, d\}\} ;$$

we define a communication function $\gamma$ such that

$$\gamma(\text{enter}_0, \text{leave}_{b,0}) = \gamma(\text{leave}_{b,0}, \text{enter}_0) = b ,$$
$$\gamma(\text{enter}_1, \text{leave}_{a,1}) = \gamma(\text{leave}_{a,1}, \text{enter}_1) = a ,$$
$$\gamma(\text{enter}_2, \text{leave}_{c,2}) = \gamma(\text{leave}_{c,2}, \text{enter}_2) = c ,$$
$$\gamma(\text{enter}_2, \text{leave}_{d,2}) = \gamma(\text{enter}_2, \text{leave}_{d,2}) = d ,$$

and $\gamma$ is undefined otherwise; and we consider the $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ expressions

$$s_0 = \partial_{\gamma}(p_0 \parallel p_1 \parallel p_2) ,$$
$$s_1 = \partial_{\gamma}(p_0 \parallel p_1' \parallel p_2) ,$$
$$s_2 = \partial_{\gamma}(p_0 \parallel p_1 \parallel p_2) ,$$

in which

$$p_0 = 1 \cdot \left(\text{enter}_0 \cdot (\text{leave}_{a,1} + \text{leave}_{c,2})\right)^* ,$$
$$p_0' = (\text{leave}_{a,1} + \text{leave}_{c,2}) \cdot \left(\text{enter}_0 \cdot (\text{leave}_{a,1} + \text{leave}_{c,2})\right)^* ,$$
$$p_1 = 1 \cdot \left(\text{enter}_1 \cdot (\text{leave}_{b,0} + \text{leave}_{d,1})\right)^* ,$$
$$p_1' = (\text{leave}_{b,0} + \text{leave}_{d,1}) \cdot \left(\text{enter}_1 \cdot (\text{leave}_{b,0} + \text{leave}_{d,1})\right)^* ,$$
$$p_2 = 1 \cdot \left(\text{enter}_2 \cdot 1\right)^* .$$

The automaton associated with $s_0$ is shown in Figure 8, with the states labelled with the above abbreviations.

![Fig. 8. An $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$-expressible automaton that is not expressible in $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$.](image)

To establish that there is no $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ expression bisimilar to $s_0$, we assume that $s$ is such a $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ expression and derive a contradiction. Note that the set $C = \{s_0, s_1\}$ is a strongly connected component in $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$. Hence, since $s_0 \not\leftrightarrow s$, by Lemma 3.2 there is a strongly connected component $C'$ in $\mathsf{ACP}_{0.1}^{*,\varnothing}(A, \gamma)$ reachable from $s$ satisfying the condition that there exist $s_0', s_1' \in C'$ such that $s_0 \not\leftrightarrow s_0'$ and $s_1 \not\leftrightarrow s_1'$.
By Proposition 6.3, $C'$ has a dominating alive exit state. From $s_0 \Leftrightarrow s'_0$ it follows that there exists $s'_2 \notin C'$ such that $s'_0 \xrightarrow{c} s'_2$ and $s_2 \Leftrightarrow s'_2$. From $s_1 \Leftrightarrow s'_1$ it follows that there exists $s''_2 \notin C'$ such that $s'_1 \xrightarrow{d} s''_2$ and $s_2 \Leftrightarrow s''_2$. So, on the one hand, both $s'_0$ and $s'_1$ are alive exit states with normed exit transitions. Now, on the one hand, $s'_0$ has a normed exit transition labelled with $c$, but it does not have a normed exit transition labelled with $d$, and, on the other hand, $s'_1$ does have a normed exit transition labelled with $d$, but it does not have a normed exit transition labelled with $c$. It follows that $s'_0$ does not dominate $s'_1$, and, on the same grounds, $s'_1$ does not dominate $s'_0$. Since all states in $C'$ are bisimilar to either $s'_0$ or $s'_1$, we conclude that $C'$ does not have a dominating exit state, and hence $s_0$ is not $\text{ACP}^{*,-\partial}_{0,1}(A,\gamma)$-expressible.

7. Every Finite Automaton is $\text{ACP}^{*}_{0,1}(A,\gamma)$-expressible

Milner (1984) observed that there exist finite automata that are not bisimilar to a finite automaton associated with a $\text{BPA}^{*}_{0,1}(A)$ expression. Our proof of Theorem 4.11 has Milner’s observation as an immediate consequence: the finite automaton associated with the $\text{PA}^{*}_{0,1}(A)$ expression used in the proof (see Figure 3) is not $\text{BPA}^{*}_{0,1}(A)$-expressible. Similarly, by Theorem 5.10, there are finite automata that are not expressible in $\text{PA}^{*}_{0,1}(A)$, and by Theorem 6.4 there are finite automata that are not expressible in $\text{ACP}^{*,-\partial}_{0,1}(A,\gamma)$.

In this section we shall prove that every finite automaton is expressible in $\text{ACP}^{*}_{0,1}(A,\gamma)$, for suitable choices of $A$ and $\gamma$, even up to isomorphism. Before we formally prove the result, let us first explain the idea informally and illustrate it with an example. The $\text{ACP}^{*}_{0,1}(A,\gamma)$ expression that we shall associate with a finite automaton will have one parallel component per state of the automaton, representing the behaviour in that state (i.e., which outgoing transitions it has to which other states and whether it is terminating). At any time, one of those parallel components, the one corresponding with the “current state,” has control. An $a$-transition from that current state to a next state corresponds with a communication between two components. We will make essential use of $\text{ACP}^{*}_{0,1}(A,\gamma)$’s facility to let the action $a$ be the result of communication.

**Example 7.1.** Consider the finite automaton in Figure 9.

Fig. 9. A finite automaton.
We associate with every state \(i \in \{0, 1, 2, 3\}\) an ACP\(^*_0,1(A, \gamma)\) expression \(p_i\) as follows:

\[
p_0 = (\text{enter}_0 \cdot (\text{leave}_{a,1} + \text{leave}_{b,1}))^* ,
\]

\[
p_1 = (\text{enter}_1 \cdot b^* \cdot (\text{leave}_{c,2}))^* ,
\]

\[
p_2 = (\text{enter}_2 \cdot (\text{leave}_{a,0} + \text{leave}_{b,3} + 1))^* ,
\]

\[
p_3 = (\text{enter}_3 \cdot 0)^* .
\]

Every \(p_i\) has an \(\text{enter}_i\) transition to gain control, and by executing a \(\text{leave}_{a,j}\) it may then release control to \(p_j\) with action \(\alpha (\alpha \in \{a, b, c\})\) as effect. We define the communication function so that an \(\text{enter}_i\) action communicates with a \(\text{leave}_{a,i}\) action, resulting in the action \(\alpha\). That is, in this particular case,

\[
\gamma(\text{enter}_0, \text{leave}_{a,0}) = \gamma(\text{leave}_{a,0}, \text{enter}_0) = a \\
\gamma(\text{enter}_1, \text{leave}_{a,1}) = \gamma(\text{leave}_{a,1}, \text{enter}_1) = a \\
\gamma(\text{enter}_1, \text{leave}_{b,1}) = \gamma(\text{leave}_{b,1}, \text{enter}_1) = b \\
\gamma(\text{enter}_2, \text{leave}_{c,2}) = \gamma(\text{leave}_{c,2}, \text{enter}_2) = c \\
\gamma(\text{enter}_3, \text{leave}_{b,3}) = \gamma(\text{leave}_{b,3}, \text{enter}_3) = b ,
\]

and \(\gamma\) is undefined otherwise. Loops in the automaton (such as the loop on state 1) require special treatment as they should not have the effect of releasing control to some other state.

Let \(p'_0\) be the result of executing the \(\text{enter}_0\)-transition from \(p_0\), i.e.,

\[
p'_0 = 1 \cdot (\text{leave}_{a,1} + \text{leave}_{b,1}) \cdot p_0 .
\]

We define the ACP\(^*_0,1(A, \gamma)\) expression that simulates the finite automaton in Figure 9 as the parallel composition of \(p'_0, p_1, p_2\) and \(p_3\), encapsulating the control actions \(\text{enter}_i\) and \(\text{leave}_{a,i}\), i.e., as

\[
\partial_{\{\text{enter}_i, \text{leave}_{a,\alpha} | i \in \{0,1,2,3\}, \alpha \in \{a,b,c\}\}} (p'_0 \parallel p_1 \parallel p_2 \parallel p_3) .
\]

We now present the technique illustrated in the preceding example in full generality. Let \(\mathcal{F} = (\mathcal{S}, \rightarrow, \uparrow, \downarrow)\) be a finite automaton. We shall associate with \(\mathcal{F}\) an ACP\(^*_0,1(A, \gamma)\) expression \(p_{\mathcal{F}}\) that has one parallel component \(p_s\) for every state \(s\) in \(\mathcal{S}\). To allow a parallel component to gain and release control, we use a collection of control actions \(C\), assumed to be disjoint from \(A\), and defined as

\[
C = \{\text{enter}_s \mid s \in \mathcal{S}\} \cup \{\text{leave}_{\alpha,t} \mid s \in \mathcal{S}, \alpha \in A\} .
\]

Gaining and releasing control is modelled by the communication function \(\gamma\) on \(A \cup C\) satisfying:

\[
\gamma(\text{enter}_s, \text{leave}_{\alpha,t}) = \gamma(\text{leave}_{\alpha,t}, \text{enter}_s) = \begin{cases} 
\alpha & \text{if } s = t; \text{ and} \\
\text{undefined} & \text{otherwise}.
\end{cases}
\]

For the specification of the ACP\(^*_0,1(A, \gamma)\) expressions \(p_s\) we need one more definition: for \(s, t \in \mathcal{S}\) we denote by \(A_{s,t}\) the set of actions occurring as the label on a transition from
Theorem 7.2. Let $s$ to $t$, i.e.,

$$A_{s,t} = \{\alpha \mid s \xrightarrow{\alpha} t\}.\$$

Now we can specify the $\text{ACP}_{0,1}(\mathcal{A},\gamma)$ expressions $p_s$ ($s \in S$) by

$$p_s = 1 \cdot (\text{enter}_s \cdot \left( \sum_{\alpha \in A_{s,s}} \alpha \right)^* \cdot \left( \sum_{t \in S} \sum_{\alpha \in A_{s,t}} \text{leave}_{\alpha,s} \, [+\, 1]_{s,t} \right))^*.$$  

(We use the notation $\sum_{P(x)} p(x)$, with $P(x)$ a unary predicate and $p(x)$ a process expression parametrised in $x$, to abbreviate the alternative composition of the elements of the set $\{p(x) \mid P(x)\}$, implicitly assuming that this set is finite. Let $\{p(x) \mid P(x)\} = \{p_1, \ldots, p_n\}$; then $\sum_{P(x)} p(x) = p_1 + \cdots + p_n$, adopting the convention that if the set $\{p(x) \mid P(x)\}$ is empty, then $\sum_{P(x)} p(x) = 0$.) By $[+\, 1]_{s,t}$ we mean that the summand + 1 is optional; it is only included if $s \downarrow$. The empty summation denotes 0. (We let $p_s$ start with 1 to later get that the finite automaton associated with the $\text{ACP}_{0,1}^*(\mathcal{A},\gamma)$ expression for $F$ is isomorphic and not just bisimilar with $F$.)

Note that, in $\text{ACP}_{0,1}(\mathcal{A},\gamma)$, every $p_s$ has a unique outgoing transition; specifically $p_s \xrightarrow{\text{enter}_s} p'_s$, where $p'_s$ denotes:

$$p'_s = (\sum_{\alpha \in A_{s,s}} \alpha)^* \cdot \left( \sum_{t \in S} \sum_{\alpha \in A_{s,t}} \text{leave}_{\alpha,s} \, [+\, 1]_{s,t} \right) \cdot p_s.$$

Now suppose that $S = \{s_0, \ldots, s_n\}$ with $\uparrow = s_0$; then we define $p_F$ by

$$p_F = \partial_C(p'_0 \parallel p_{s_1} \parallel \cdots \parallel p_{s_n}).$$

Clearly, the construction of $p_F$ works for every finite automaton $F$. The bijection defined by $s_i \mapsto \partial_C(p_{s_0} \parallel \cdots \parallel p_{s_{i-1}} \parallel p'_{s_i} \parallel p_{s_{i+1}} \parallel \cdots \parallel p_{s_n})$ is an isomorphism from $F$ to the automaton associated with $p_F$ by the operational semantics. We shall refer to $p_F$ as the $\text{ACP}_{0,1}^*(\mathcal{A},\gamma)$ expression associated with $F$.

Theorem 7.2. Let $F$ be a finite automaton, and let $p_F$ be its associated $\text{ACP}_{0,1}(\mathcal{A},\gamma)$ expression. The automaton associated with $p_F$ by the operational rules for $\text{ACP}_{0,1}(\mathcal{A},\gamma)$ is isomorphic to $F$.

Proof. The bijection defined by $s_i \mapsto \partial_C(p_{s_0} \parallel \cdots \parallel p_{s_{i-1}} \parallel p'_{s_i} \parallel p_{s_{i+1}} \parallel \cdots \parallel p_{s_n})$ is an isomorphism from $F$ to the automaton associated to $p_F$ by the operational semantics in $\text{ACP}_{0,1}^*(\mathcal{A},\gamma)$.

Corollary 7.3. For every finite automaton $F$ there exists an instance of $\text{ACP}_{0,1}(\mathcal{A},\gamma)$ with a suitable finite set of actions $\mathcal{A}$ and a handshaking communication function $\gamma$ such that $F$ is $\text{ACP}_{0,1}^*(\mathcal{A},\gamma)$-expressible up to isomorphism.

8. Conclusion

In this paper we have investigated the effect on the expressiveness of regular expressions modulo bisimilarity if different forms of parallel composition are added. We have
established an expressiveness hierarchy that can be briefly summarised as:

\[ \text{BPA}_0^\ast(A) \prec \text{PA}_0^\ast(A) \prec \bigcup_{\gamma} \text{ACP}^{\ast}_{0,1}(A,\gamma) \prec \bigcup_{\gamma} \text{ACP}_{0,1}^\ast(A,\gamma). \]

Furthermore, while not every finite automaton can be expressed modulo bisimilarity with a regular expression, it suffices to add a form of ACP(A,\gamma)-style parallel composition, with handshaking communication and encapsulation, to get a language that is sufficiently expressive to express all finite automata modulo bisimilarity. These results should be contrasted with the well-known result from automata theory that every non-deterministic finite automaton can be expressed with a regular expression modulo language equivalence.

As an important tool in our proof, we have characterised the strongly connected components in BPA_0^\ast(A), PA_0^\ast(A), and ACP_0^\ast(A,\gamma). An interesting open question is whether the given characterisations are complete, in the sense that a finite automaton is expressible in BPA_0^\ast(A), PA_0^\ast(A), or ACP_0^\ast(A,\gamma) iff all its strongly connected components satisfy the respective characterisations. If so, then our characterisations would constitute a useful complement to the characterisation of Baeten et al. (2007) and perhaps lead to a more efficient algorithm for deciding whether a non-deterministic automaton is expressible.

Bergstra et al. (2001) prove that every finite transition system without intermediate termination can be denoted in ACP_0^\ast(A,\gamma) up to branching bisimilarity (Glabbeek & Weijland 1996), and that ACP_0^\ast(A,\gamma) modulo (strong) bisimilarity is strictly less expressive than ACP_0^\ast(A,\gamma). In contrast, we have established that every finite automaton (i.e., every finite transition system not excluding intermediate termination) is denoted by an ACP_0^\ast(A,\gamma) expression. It follows that ACP_0^\ast(A,\gamma) and ACP_0^\ast(A,\gamma) are equally expressive.

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References
Our process theory $ACP_{0,1}^*(A,\gamma)$ is grounded in Bergstra & Klop’s (1984) $ACP(A,\gamma)$, but we have omitted the operations $\parallel$ and $\mid$ introduced by Bergstra and Klop to facilitate a finite axiomatisation of the theory. We establish below that they do not add expressiveness in our setting of $ACP_{0,1}^*(A,\gamma)$ with Kleene star instead of general recursion.

We shall in this appendix assume that the binary operations $\parallel$ and $\mid$ are included in the syntax of $ACP_{0,1}^*(A,\gamma)$ and that the operational rules in Table 2 are added to those in Table 1 on page 5.

<table>
<thead>
<tr>
<th>Rule Number</th>
<th>Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>$p \xrightarrow{a} p'$</td>
</tr>
<tr>
<td></td>
<td>$p \parallel q \xrightarrow{a} p' \parallel q$</td>
</tr>
<tr>
<td>19</td>
<td>$p \xrightarrow{a} p'$</td>
</tr>
<tr>
<td></td>
<td>$q \xrightarrow{\gamma(a,b)} q'$</td>
</tr>
<tr>
<td></td>
<td>$\gamma(a,b)$ is defined</td>
</tr>
<tr>
<td></td>
<td>$p \parallel q \xrightarrow{\gamma(a,b)} p' \parallel q'$</td>
</tr>
<tr>
<td>20</td>
<td>$p \parallel q \xrightarrow{\gamma(a,b)} p' \parallel q'$</td>
</tr>
</tbody>
</table>

Table 2. Operational rules for $\parallel$ and $\mid$, with $a \in A$.

We shall prove that the process theories $ACP_{0,1}^*(A,\gamma)$ with and without $\parallel$ and $\mid$ are equally expressive in a strong sense: modulo bisimilarity the operations $\parallel$ and $\mid$ can be...
eliminated from $\text{ACP}^*_{0,1}(A, \gamma)$ expressions. We proceed as follows: first we establish that $\parallel$ and $|$ can be eliminated from $\text{ACP}^*_{0,1}(A, \gamma)$ expressions of the form $p \parallel q$ or $p \mid q$ provided that $\parallel$ and $|$ do not occur in $p$ and $q$. Then we recall that bisimilarity is a congruence. Finally, we combine these facts to conclude that $\parallel$ and $|$ can be eliminated from all $\text{ACP}^*_{0,1}(A, \gamma)$ expressions.

According to the following lemma, occurrences of $\parallel$ can be eliminated from $\text{ACP}^*_{0,1}(A, \gamma)$ expressions.

**Lemma A.1.** Let $p$ and $q$ be $\text{ACP}^*_{0,1}(A, \gamma)$ expressions. If $p$ and $q$ do not contain occurrences of $\parallel$, then there exists a process expression $r$ without occurrences of $\parallel$ such that $p \parallel q \leftrightarrow r$.

**Proof.** If $\parallel$ and $|$ are added to the syntax, then the transition system space $\text{ACP}^*_{0,1}(A, \gamma)$ is still regular (cf. Lemma 2.1 on page 6). Hence, the set

$$\text{Der}(p) = \{(a,p') \mid p \xrightarrow{a} p'\}$$

is finite. We define $r$ by

$$r = \sum_{(a,p') \in \text{Der}(p)} a \cdot (p' \parallel q).$$

Clearly, $r$ has no occurrences of $\parallel$, and it is straightforward to verify that the binary relation

$$\{(p \parallel q, r), (r, p \parallel q) \} \cup \{(p, p) \mid p \text{ a process expression}\}$$

is a bisimulation relation from $\text{ACP}^*_{0,1}(A, \gamma)$ to $\text{ACP}^*_{0,1}(A, \gamma)$, so $p \parallel q \leftrightarrow r$. \qed

According to the following lemma, occurrences of $|$ can be eliminated from $\text{ACP}^*_{0,1}(A, \gamma)$ expressions too.

**Lemma A.2.** Let $p$ and $q$ be process expressions. If $p$ and $q$ do not contain occurrences of $\parallel$, then there exists a process expression $r$ without occurrences of $\parallel$ such that $p \parallel q \leftrightarrow r$.

**Proof.** If $\parallel$ and $|$ are added to the syntax, then the transition system space $\text{ACP}^*_{0,1}(A, \gamma)$ is still regular (cf. Lemma 2.1 on page 6). Hence, the sets

$$\text{Der}(p) = \{(a,p') \mid p \xrightarrow{a} p'\}$$

and

$$\text{Der}(q) = \{(b,q') \mid q \xrightarrow{b} q'\}$$

are finite. Define the set $\text{Der}(r)$ by

$$\text{Der}(r) = \{((\gamma(a,b), p', \parallel q')) \mid (a,p') \in \text{Der}(p), (b,q') \in \text{Der}(q), \text{ and } \gamma(a,b) \text{ is defined}\},$$

and define $r$ by

$$r = \sum_{(c,r') \in \text{Der}(r)} c \cdot r'.$$
Clearly, \( r \) has no occurrences of \(|\) and it is straightforward to verify that the binary relation

\[
\{(p \mid q, r), (r, p \mid q)\} \cup \{(p, p) \mid p \text{ a process expression}\}
\]

is a bisimulation relation from \( \text{ACP}_{0,1}^* (A, \gamma) \) to \( \text{ACP}_{0,1}^* (A, \gamma) \), so \( p \mid q \leftrightarrow r \). \( \square \)

To be able to apply the previous two lemmas in the context of a larger \( \text{ACP}_{0,1}^* (A, \gamma) \) expression, we need to know that bisimilarity is a congruence on \( \text{ACP}_{0,1}^* (A, \gamma) \) expressions.

**Lemma A.3.** The relation \( \leftrightarrow \) is a congruence on the set of \( \text{ACP}_{0,1}^* (A, \gamma) \) expressions.

**Proof.** It is well-known that \( \leftrightarrow \) is an equivalence. Moreover, the operational rules in Tables 1 and 2 are all in the path format, so by Theorem 5.4 of Baeten & Verhoef (1993) bisimilarity is compatible with the syntax of \( \text{ACP}_{0,1}^* (A, \gamma) \). \( \square \)

Now we are in a position to establish the elimination \( || \) and \( | \) from all \( \text{ACP}_{0,1}^* (A, \gamma) \) expressions.

**Proposition A.4.** For every \( \text{ACP}_{0,1}^* (A, \gamma) \) expression \( p \) there exists an \( \text{ACP}_{0,1}^* (A, \gamma) \) expression \( q \) such that \( p \leftrightarrow q \).

**Proof.** By a straightforward induction on the structure of \( p \), using Lemma A.3 for applying the induction hypothesis, Lemma A.1 for the case that \( p \) is of the form \( p_1 \parallel p_2 \), and Lemma A.2 for the case that \( p \) is of the form \( p_1 \mid p_2 \). \( \square \)

Similarly, it can be shown that adding \( || \) to \( \text{PA}_{0,1}^* (A) \) or \( || \) and \( | \) to \( \text{ACP}_{0,1}^* (A, \gamma) \) does not add expressiveness to the respective process theories.