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Testing for Refinement in CSP

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Abstract. CSP is a well-established formalism for modelling and verification of concurrent reactive systems based on refinement. Consolidated denotational models and an effective tool have encouraged much work on algebraic reasoning and model checking. Testing techniques based on CSP models, however, have not been widely explored, and in this paper we take a first step by instantiating a long standing theory of formal testing to CSP. We identify the testability hypothesis that we consider necessary to make the use of CSP feasible, define test sets that we prove to be exhaustive with respect to traces and failures refinement, and consider optimisations, inputs and outputs, and selection strategies. All our results are proved in terms of the CSP denotational models. They are a sound foundation for the development of test-generation techniques.

1 Introduction

It is well accepted that formal specifications can be useful bases for software testing; we refer to [5, 10, 2, 3, 1, 16] among many other pioneering papers and surveys. In spite of that, testing based on CSP [23, 15], which is a popular formal notation for specification and verification of concurrent systems, has not been widely explored. In this paper, we establish the foundations of CSP-based testing by instantiating a well-established theory of formal testing.

Even though it has been recognised for a while that formal models can bring much to software testing, embedding implementation testing within a formal framework is far from being obvious. We test a system: a system is not a formula, even if it can be (partially) described as such. Thus, testing is related to, but very different from proof of correctness based on the program text using, for example, an assertion technique. Similarly, testing is different from model checking, where verifications are based on a known model of the system: when testing, the model corresponding to the system under test is unknown. If it was known, testing would not be necessary... Moreover, it is sometimes difficult to observe the state of the system under test [5, 11, 16]. These points have been successfully circumvented in several testing methods that are based on formal specifications (or models) and on conformance relations that precisely state what it means for a system under test to satisfy a specification [6–8, 28, 13, 12, 18, 17].

The gap between systems and models is generally taken into account by explicit assumptions on the systems under test [5, 1, 16] that are called “testability

hypotheses” in [1] or “test hypotheses” in [4]. Such assumptions are fundamental in the proof that the success of the test set derived from the specification establishes the conformance relation. Moreover, they provide hints on complementary tests or proofs that may be necessary to ensure this equivalence.

CSP provides, in addition to a formal semantics of communicating processes, formal definitions of notions of refinements similar to the conformance relations used in specification-based testing or model-based testing. Peleska and Siegel [21, 22] have already studied and applied CSP-based testing. They have not, however, addressed the issue of the gap between the system under test and the CSP model that it defines. The practical test sets they propose in [22] are inspired by, but not in direct correspondence with their theoretical definitions.

Schneider [24] defines a partition that classifies refusable and non-refusable events, and high-level and low-level events, for the purposes of modelling security applications in CSP. In that work, two conformance relations based on testing are defined, and Schneider shows how model checking can be used to establish such relations. In our work, on the other hand, we are interested in refinement.

The work in [26] recognises the potential impact of the interaction of a system with its environment on the reliability of results on refinement. It aims at supporting the validation of (implicit) assumptions about the environment in a CSP model. For that, mutation testing techniques are applied to a CSP specification of the system, and the mutants that satisfy the properties of interest are collected and used as a basis for the clarification of requirements.

In this paper, we state the testability hypotheses that are associated with the use of CSP. Moreover, we formalise accurately the kind of observations (traces and refusals) that must be done when performing test experiments derived from a CSP specification. It leads to a novel formulation of the tests and of their verdicts. We give algebraic proofs that getting the right observations when running these tests is equivalent to establishing traces or failures refinement.

The paper is organised as follows. In the next section, we give a brief introduction to CSP, and in Section 3 we discuss the consequences of using a process algebra specification as a basis for testing. Our main contributions come in Section 4, where we introduce our testability hypotheses and their consequences, and in Section 5, where we give our exhaustive test sets. The following sections discuss the impact of our approach: in Section 6, we discuss possible optimisations of our tests, in Section 7 we discuss possible test selection criteria, and in Section 8, we discuss the issues raised by the treatment of inputs and outputs in CSP. Finally, we conclude in Section 9 with a summary of our results, an a discussion of related and future work.

2 A few things on CSP

Here we briefly recall the syntax of CSP, and some important points of its semantics and notions of refinement. More information can be found in [23].

2.1 Main CSP operators

In CSP, a system is modelled as a process that can interact with its environment via a number of events. CSP models describe a collection of processes and their patterns of interactions. The unit of interaction is an event which processes perform and on which they may synchronise; the *occurrence* of events is atomic. The set of (external) events of a process P is denoted αP .

There are two basic processes: *STOP* is a deadlocked process, and *SKIP* is the terminating process. The process $a \rightarrow P$ can perform an event a and then behave as P . The external choice, $P_1 \square P_2$, is initially prepared to behave either as P_1 or as P_2 , with the choice being made on occurrence of the first event. Nondeterminism is modelled by an internal choice, $P_1 \sqcap P_2$, which is a process that can arbitrarily choose to behave as either P_1 or P_2 .

Processes can also be combined in sequence, using the operator $;$, or in parallel. CSP provides a number of operators for parallelism; here we use the alphabetised parallelism: $P_1 \parallel A \parallel P_2$, which executes P_1 and P_2 concurrently, requiring that they synchronise on events that are in the set A .

Events can be external, that is, observable and controllable by the environment, or internal. Using the hiding operator, like in $P \setminus A$, we define a process that behaves like P , but whose events in the set A are internal.

A simple example, which we use later on, is given below: a process *Counter*₂ that counts from 0 to 2, and is defined in terms of the processes C_1 and C_2 .

$$\begin{aligned} \text{Counter}_2 &= \text{add} \rightarrow C_1 \\ C_1 &= \text{add} \rightarrow C_2 \square \text{sub} \rightarrow \text{Counter}_2 \\ C_2 &= \text{sub} \rightarrow C_1 \end{aligned}$$

The events in $\alpha \text{Counter}_2$ are *add* and *sub*, which model requests to add to or subtract from the counter.

In CSP, inputs and outputs are not primitive concepts; they are modelled using events whose names are composite. A classical example is a copying process *Replicator*, which takes an input x from a channel c and sends it back.

$$\text{Replicator} = c?x \rightarrow c!x \rightarrow C$$

If we assume that the type of x is the rather small set $\{0, 1, 2\}$, then we have the events $c.0$, $c.1$, and $c.2$. In this case, the above definition of *Replicator* is just an abbreviation for the following definition in terms of these basic events.

$$\begin{aligned} \text{Replicator} &= c.0 \rightarrow c.0 \rightarrow C \\ &\square \\ &c.1 \rightarrow c.1 \rightarrow C \\ &\square \\ &c.2 \rightarrow c.2 \rightarrow C \end{aligned}$$

In general, an input like $c?x \rightarrow P(x)$ is an abbreviation for an external choice over processes $c.v \rightarrow P(v)$, for all possible values v for x . Potentially, this is an infinite external choice. An output event $c!e$, on the other hand, is just another name for the event $c.v$, where v is the value of e .

2.2 Semantics and refinement

There are three well-established semantic models of CSP: the traces, the (stable) failures, and the failures-divergences models. The traces model characterises a process P by its set $traces(P)$ of traces: finite sequences of events which it can perform. It is a subset of $((\alpha P) \cup \{\checkmark\})^*$; A^* is the set of finite sequences of elements of A . The special event \checkmark records termination. The empty trace is $\langle \rangle$. The set of all events, except only for \checkmark , is Σ ; the set including \checkmark is denoted Σ^\checkmark . In the sequel, we sometimes consider traces as processes: the finite trace a_1, a_2, \dots corresponds to the process $a_1 \rightarrow a_2 \rightarrow \dots \rightarrow SKIP$.

As usual we write P/s to describe the behaviour of the process P after one of its traces s , and $initials(P/s)$ for the set of events performable by P after s . In fact, $initials$ is defined for any process P , and can be characterised in terms of its traces as follows [23, page 197].

$$initials(P) = \{ a : \Sigma^\checkmark \mid \langle a \rangle \in traces(P) \}$$

For a trace s of a process P and a subset $A = \{a_1, \dots, a_n\}$ of αP , the pair (s, A) is a failure for P if, and only if, after performing s , P may refuse all events of A : in other words, $P \parallel \alpha P \parallel (s; (a_1 \rightarrow P_1 \square \dots \square a_n \rightarrow P_n))$ may deadlock just after s . For *Counter*₂, the set of failures includes the following elements.

$$\begin{aligned} & (\langle \rangle, \{sub\}), (\langle \rangle, \emptyset), \\ & (\langle add \rangle, \emptyset), \\ & (\langle add, add \rangle, \{add\}), (\langle add, add \rangle, \emptyset), \\ & (\langle add, sub \rangle, \{sub\}), (\langle add, sub \rangle, \emptyset), \\ & (\langle add, add, sub \rangle, \emptyset), \\ & \dots \end{aligned}$$

The set $failures(P)$ containing all failures of P is subset closed: for instance, if P may deadlock when the choice among the events $\{a, b\}$ is proposed by its environment after a trace s , it may deadlock as well if only a or b is proposed. The traces of P can be defined from its failures as follows.

$$traces(P) = \{ t : \Sigma^\checkmark^* \mid (t, \emptyset) \in failures(P) \}$$

The set $divergences(P)$ is the set of traces of P that lead to divergent behaviour, that is, an infinite sequence of internal events, plus all the extensions of those traces. The canonical semantics of CSP is given by the failures-divergences model; it represents a process P by the two sets $failures(P)$ and $divergences(P)$.

Here, we assume that specifications and systems are divergence free. A divergent specification is necessarily a mistake. Also, when testing, divergences raise problems of observability; generally, it is not possible to distinguish a divergent from a deadlocked system using testing. Therefore, we identify divergence with deadlock in the models of the systems under test, so that the models are divergence free; most authors circumvent the problem of observability in this way. If the system under test is divergent, the divergence is detected as a (probably forbidden) deadlock and reported as such by the verdict of the tests.

We consider two refinement relations between CSP processes: traces and failures refinement. A process P is trace-refined by a process Q , that is $P \sqsubseteq_T Q$, if, and only if, $traces(Q) \subseteq traces(P)$. For failures refinement, $P \sqsubseteq_F Q$, we require that $failures(Q) \subseteq failures(P)$, that is, Q refines P with respect to failures if, and only if, all its possible traces are traces of P , and Q may refuse a set of events and deadlock after a trace only if P may.

Remark 1. The first refinement relation is restrictive: it states that there are no observable behaviours of the refined process that are not behaviours of the original process. It accepts the idle process $STOP$ as a trace refinement of any other process. The second refinement relation is still restrictive on traces, but prescriptive on acceptances: it states that the refined process can only refuse to do something when the original process may refuse the same thing in the same situation. In this case, there are forbidden behaviours and mandatory behaviours.

For divergence-free processes, failures refinement as described above corresponds to the refinement relation in the canonical model of CSP: failures-divergences refinement, which is defined as follows.

$$P \sqsubseteq_{FD} Q \hat{=} failures(Q) \subseteq failures(P) \wedge divergences(Q) \subseteq divergences(P)$$

In CSP, failures refinement is defined for the stable-failures model, and not for the failures-divergences model as above. In the stable-failures model, a process is represented by its set of traces and its set of failures, that is, we have a separate record of the traces, independent of the failures. This is because, in this model, failures are only recorded for stable states, so that traces that lead to divergence are not in any of the failures. For the stable-failures model, failures refinement requires subset inclusion of both traces and failures.

In the absence of divergence, however, the failures in the stable-failures model are exactly those of the failures-divergences model, which contain a failure for all traces of the process [23, page 215]. In this case, failures inclusion, as required above in our definition of failures refinement, implies traces inclusion. In summary, for divergence-free processes, our definition of failures refinement is equivalent to the standard definition of failures refinement in CSP.

Furthermore, since the set of divergences of divergence-free processes are empty, failures-divergences refinement corresponds to failures refinement. In summary, our definition of failures refinement is the notion of refinement in the canonical model of CSP, when we are restricted to divergence-free processes.

3 Process-algebra based testing

Given a specification SP and a system under test (SUT), any testing activity is, explicitly or not, based on a satisfaction relation (also called conformance relation): $SUT \text{ sat } SP$. The subject of the test is an executable system. A system is a dynamic entity. It raises tricky issues such as observability and controllability, and is sometimes submitted to peculiar physical constraints. The only way to observe it is to interact via some specific (and often limited) interface.

To test a system against a process specification, we need tests (more exactly tester processes) built on the same alphabet of events as the specification (possibly enriched by some special symbols). The execution of a given test consists in running it and the *SUT* in parallel.

The verdict about the success or not of a test execution depends on the observations that can be made, and it is based on the satisfaction relation. Most testing methods based on process algebras consider that two kinds of observations are possible: external events, and deadlock (that is, refusal of some external events). Deadlock is observed via time-out mechanisms: it is assumed that if the *SUT* does not react after a given time limit, it is blocked.

The tests are derived from the specification on the basis of the satisfaction relation, and often on the basis of some additional knowledge of the *SUT* and of its operational environment called *testability hypothesis*. One advantage of such a formal framework is that it makes it possible to define test sets that are unbiased and valid: they accept any *SUT* satisfying the specification and the testability hypothesis, and they reject any *SUT* that does not. Such test sets are called *exhaustive* in [11] or *complete* by other authors [3].

Exhaustive test sets are often infinite, or too large to be used in practice, but they are used as references for selecting finite, practical, test subsets according to a variety of criteria, such as additional hypotheses on the *SUT* [1], coverage of the specification [5, 16], or test purposes [9].

4 Testing versus refinement: testability hypotheses

Work on testing processes is traditionally based on labelled transition systems or finite state machines. To recast these results for CSP, the obvious route is to consider its operational semantics. However, there is a formal link between the operational and the denotational semantics of CSP. The main concepts usually associated with the operational semantics, like sets of initials and refusals, are also defined in terms of the denotational semantics.

This is most convenient to establish a relationship between testing and refinement. The definitions of refinement based on the denotational semantics are very simple: just subset inclusion, as presented above. It is fortunate that we are able to discuss testing notions based on the usual operational notions, but that we have a clear link to the denotational semantics. When considering test criteria and test selection, though, it is necessary to refer to the operational semantics. For instance, the most popular selection criterion is transition coverage: explicit notions of states and transitions are needed to formulate it.

The refinement relations presented in Section 2.2 are natural candidates for CSP-based testing. They are, however, relations between *CSP* process, and the *SUT* is not a *CSP* process. A classical way of overcoming this difficulty is to assume that *the SUT behaves like some unknown CSP process*; this is our first testability hypothesis. With this assumption, we can then require that this process is a refinement of the *CSP* specification. We define that a system *P* behaves like a CSP process *Q* to mean that, in any environment, running *P*

or running Q yields the same set of observations. If P and Q were both CSP processes, then behavioural equivalence would be characterised as refinement in both directions, but P is not a CSP process; it is a system.

In more detail, if SUT_{CSP} denotes the unknown *CSP* process that behaves as the *SUT*, we can consider the satisfaction relation $SP \sqsubseteq_F SUT_{CSP}$ based on failures refinement. In the sequel, we write *SUT* instead of SUT_{CSP} when there is no ambiguity. The use of failures refinement as a satisfaction relation has been studied in different frameworks, with various names and notations since the original definition of testing equivalence in [19]; *testing preorder*, *failure preorder*, \leq_{te} , *red*, *conf* are examples of the terminology that has been adopted.

The testability hypothesis requires that events of the specification abstract operations are perceived as atomic and of irrelevant duration in the *SUT*. It is necessary to ensure in some way that this requirement is fulfilled, for example, by developing wrappers, or performing some complementary proofs or tests.

Remark 2. It is interesting to note that, similarly, testing methods based on Finite State Machine (FSM) descriptions assume that the *SUT* behaves as an FSM with the same number of states as the specification, or a known number of states [16]. Likewise, methods based on IO-automata or IO-Transition Systems assume that the *SUT* behaves as an IO-automata: it is input-enabled, that is, always ready to accept any input [28]. Analogously, methods based on algebraic specifications assume that the *SUT* behaves as a many-sorted algebra [1].

Our second testability hypotheses is related nondeterminism in the *SUT* and its influence on the verdict after test executions. This hypothesis, sometimes called the *complete testing assumption*, postulates that *there is some known integer k such that, if a test experiment is performed k times, then all possible behaviours are observed*. The issue of the number of test executions is a classical problem in black-box testing of nondeterministic systems. Its choice is generally based on empirical knowledge of the system, as, for example, its level of internal parallelism that may give rise to nondeterminism, and the length of the test. Without such hypotheses, it is hopeless to get a meaningful conclusion after a test campaign. For some hints, see [12], and for recent variants, see [14].

An example is an *SUT* that reads the system *clock*, and based on whether the time is an odd or an even number, performs the *even* or *odd*. Using the first testability hypothesis, we assume that it behaves like the CSP process below.

$$\begin{aligned} CReader = \text{clock}?t \rightarrow & \mathbf{if} \text{ even}(t) \\ & \mathbf{then} (\text{even} \rightarrow SKIP) \\ & \mathbf{else} (\text{odd} \rightarrow SKIP) \end{aligned}$$

If we cannot observe the *clock*, then the behaviour of the *SUT* is more accurately described by the CSP process $CReader \setminus \{clock\}$, which, using the algebraic laws of CSP, we can show to be equal, in the failures-divergences model, to the nondeterministic process $\text{even} \rightarrow SKIP \sqcap \text{odd} \rightarrow SKIP$. Such *SUT* does not satisfy, according to the semantics of nondeterminism in CSP, our second testability hypothesis: no *SUT* that behaves like a nondeterministic CSP process

does, since nondeterminism in CSP is modelled as a completely arbitrary choice, with no guarantee of balanced behaviour for any value of k . Extra knowledge of the performance of the *SUT*, and of the system *clock*, however, may allow us to conclude that, if the system is executed, for instance, sixty times in a single minute, it is guaranteed to read an even and an odd time at least once.

Such considerations are beyond what we aim at formalising in this paper. For the above example, for instance, we can say that $CReader \setminus \{\text{clock}\}$ is not an accurate model of the *SUT*. The extra knowledge of the performance of the *SUT* and of the clock means that we know that it actually behaves like a deterministic, in the sense of CSP, process whose description requires the formalisation of a notion of time, and properties of the clock. In other words, we accept the restriction imposed by the second testability hypothesis that, in the CSP sense, the *SUT* is deterministic, but point out that determinism may come from the observation of events that are not necessarily expected to be in the alphabet of the specification. In our example, these events are, for instance, the passage of time and the system clock.

These considerations are not relevant for works based, for example, on finite state machines, where nondeterminism is not necessarily arbitrary. In CSP, nondeterminism captures a notion of abstraction relevant for system development, and, therefore, refinement. If there is any factor that allows us to make any conclusion about the balance of nondeterministic behaviour, this means that, in the CSP sense, the system is not really nondeterministic.

5 Tests and exhaustive test sets

Failures refinement can be expressed in terms of traces refinement and a well-studied satisfaction relation [3]: the *conf* conformance relation (cf. Proposition 3.13.1 in [27]). In our setting, *conf* can be defined as follows.

$$Q \text{ conf } P \hat{=} \forall t : \text{traces}(P) \cap \text{traces}(Q) \bullet \text{Ref}(Q, t) \subseteq \text{Ref}(P, t) \\ \text{where } \text{Ref}(P, t) \hat{=} \{ X \mid (t, X) \in \text{failures}(P) \}$$

The above definition of $\text{Ref}(P, t)$ is compatible with the definition of $\text{refusals}(P)$ in CSP, for the process P/t [23, pages 94,197].

The following theorem establishes the relationship between failure refinement, traces refinement, and *conf*.

Theorem 1. $(P \sqsubseteq_F Q) \Leftrightarrow (P \sqsubseteq_T Q \wedge Q \text{ conf } P)$

Proof

$$P \sqsubseteq_T Q \wedge Q \text{ conf } P$$

$$\Leftrightarrow \text{traces}(Q) \subseteq \text{traces}(P) \wedge \quad [\text{definitions of } \sqsubseteq_F \text{ and } \text{conf}] \\ \forall t : \text{traces}(Q) \bullet \{ X \mid (t, X) \in \text{failures}(Q) \} \subseteq \{ X \mid (t, X) \in \text{failures}(P) \}$$

$$\Leftrightarrow \text{traces}(Q) \subseteq \text{traces}(P) \wedge \quad [\text{property of sets}] \\ \forall t : \text{traces}(Q); X \bullet (t, X) \in \text{failures}(Q) \Rightarrow (t, X) \in \text{failures}(P)$$

$$\begin{aligned}
&\Leftrightarrow \text{traces}(Q) \subseteq \text{traces}(P) \wedge && \text{[definition of } \text{traces}(Q)\text{]} \\
&\quad \forall t, X \bullet (\exists X \bullet (t, X) \in \text{failures}(Q)) \Rightarrow \\
&\quad \quad ((t, X) \in \text{failures}(Q) \Rightarrow (t, X) \in \text{failures}(P)) \\
&\Leftrightarrow \text{traces}(Q) \subseteq \text{traces}(P) \wedge && \text{[predicate calculus]} \\
&\quad \forall t, X \bullet (t, X) \in \text{failures}(Q) \Rightarrow (t, X) \in \text{failures}(P) \\
&\Leftrightarrow \text{traces}(Q) \subseteq \text{traces}(P) \wedge \text{failures}(Q) \subseteq \text{failures}(P) && \text{[property of sets]} \\
&\Leftrightarrow \text{failures}(Q) \subseteq \text{failures}(P) && \text{[definition of } \text{traces}\text{]} \\
&\Leftrightarrow P \sqsubseteq_F Q && \text{[definition of } \sqsubseteq_F\text{]} \\
&\square
\end{aligned}$$

This theorem justifies the suggestion in [27] that traces refinement and *conf* can be checked separately. It should be possible to devise testing strategies that check trace inclusion and *conf* together. This could give rise to more efficient testing strategies, although they would be based on more complex tests and more complex definitions of verdict. For the purposes of studying the relationship between tests and refinement, it is more useful to keep the tests simple. In this section we first study how to test a system with respect to trace containment. Then we address the problem of testing against refusal containment. Optimisations are considered later on in Section 6.

5.1 Testing against traces refinement

Since trace refinement prescribes that $\text{traces}(SUT) \subseteq \text{traces}(SP)$, but not the reverse, a testing strategy does not need to test that a *SUT* can execute the traces of *SP*. It is sufficient to test it against those traces in $\alpha(SP)^{\check{*}}$ that are not traces of *SP* and to check that they are refused. Moreover, it is sufficient to consider the minimal prefixes of forbidden traces that are forbidden themselves. For example, if after a trace *abc*, the event *d* is forbidden, then *abcd*, and *abcdb*, for example, are also forbidden, but we only need to consider *abcd*. On the other hand, if *abd* is also forbidden, we also check that it is refused.

Formally, we define a test set that proposes to the *SUT* the following traces.

$$\{s \frown \langle a \rangle \mid s \in \text{traces}(SP) \wedge a \notin \text{initials}(SP/s)\}$$

For one test execution, the verdict is determined as follows.

- If the trace *s*, followed by a deadlock is observed, then the test execution is said to be a *success*.
- If a trace $s \frown a$ is observed, the result of the test is a *failure*.
- If a strict prefix of *s* followed by a deadlock is observed, then the test execution is said to be *inconclusive*; the trace *s* has not been executed by the *SUT*, and this is quite acceptable from the definition of traces refinement.

As mentioned in Section 4, if the *SUT* is nondeterministic, then several execu-

tions of the same test must be performed and a global verdict is reached based on such a set of executions. When the SUT is known to be deterministic, there is no need for several executions of any of the tests, and the SUT passes a test as soon as the verdict is either successful or inconclusive, and not a failure.

When the SUT is nondeterministic, the following global verdict for several executions of the same test is recorded.

- If there is one execution with a failure verdict, the SUT does not pass the test.
- If for all the test executions the verdict is either success or inconclusive, the SUT passes the test.

Remark 3. The idea of basing the test set on the pairs (s, a) , with $s \in \text{traces}(SP)$ and $a \notin \text{initials}(SP/s)$, is inspired on the work of Peleska and Siegel [21], where it is proved that based on this set of pairs, it is possible to detect all violations of traces refinement, and that this is the minimal set of pairs with this property. The notions of test and verdict that we present below, however, are slightly different, and also, we give an algebraic proof of the exhaustivity of the test set.

As mentioned in Section 3, a test execution is a run of the SUT and a test process T in parallel; we describe this in CSP as $(SUT \parallel \alpha SP) \setminus \alpha SP$. The synchronisation set, which is the interface of the system as defined in the specification, is hidden; so, the external events of SUT are internal in a test execution. This means that synchronisation between the SUT and the test proceeds immediately, and cannot be affected by the test execution environment.

On the other hand, this also means that direct observation of traces is not possible in such test executions. Thus, we introduce three special events, *pass*, *fail*, and *inc*, in the alphabet of the test in order to perform on-the-fly verdict. Using these events, we have a very direct characterisation in CSP of the verdict of a single test execution as described above.

For a finite trace $s = a_1, a_2, \dots, a_n$ and an event a , we define the CSP test process $T_T(s, a)$ as follows.

$$T_T(s, a) = inc \rightarrow a_1 \rightarrow inc \rightarrow a_2 \rightarrow inc \dots a_n \rightarrow pass \rightarrow a \rightarrow fail \rightarrow STOP$$

Formally, we can define it as shown below.

$$\begin{aligned} T_T(\langle \rangle, a) &= pass \rightarrow a \rightarrow fail \rightarrow STOP \\ T_T(\langle \checkmark \rangle, a) &= pass \rightarrow a \rightarrow fail \rightarrow STOP \\ T_T(\langle b \rangle \frown s, a) &= inc \rightarrow b \rightarrow T_T(s, a) \end{aligned}$$

Extending s with a is supposed to lead to an invalid trace; and the test aims at ruling it out. The event \checkmark , if it happens, is final [23, page 143], and only marks termination. So, no event should occur after it.

The execution of a test for a given SUT , against a specification SP , is described by the CSP process below.

$$\text{Execution}_{SUT}^{SP}(T) = (SUT \parallel \alpha SP) \setminus \alpha SP$$

The verdict of the execution is given by the last event observed among *pass*, *fail*,

and *inc* before deadlock.

Remark 4. Depending on the precision required for the verdict and on some knowledge of the *SUT*, it is possible in some cases to use only one or two events among *pass*, *fail*, and *inc*. If the *SUT* is deterministic, for instance, there are no inconclusive verdicts, and *inc* can be eliminated. In fact, in our case, since we are testing for absence of forbidden traces, we can eliminate *inc* in this way. If any prefix of a tested trace is observed, the test is successful (due to the prefix closure of the sets of traces and the definition of trace refinement). Our use of the three events, however, gives a direct model of verdict for a single test execution.

We now define an exhaustive test set for trace refinement.

$$Exhaust_T(SP) = \{ T_T(s, a) \mid s \in traces(SP) \wedge a \notin initials(SP/s) \}$$

Testing of termination is covered because it is signalled by the event \checkmark that is explicitly included in the traces.

As an example, we consider the process *Counter₂* from Section 1. The set $Exhaust_T(Counter_2)$ contains the following tests.

$$\begin{aligned} T_T(\langle \rangle, sub) &= pass \rightarrow sub \rightarrow fail \rightarrow STOP \\ T_T(\langle add, add \rangle, add) &= inc \rightarrow add \rightarrow inc \rightarrow add \rightarrow pass \rightarrow add \rightarrow fail \rightarrow STOP \\ T_T(\langle add, sub \rangle, sub) &= inc \rightarrow add \rightarrow inc \rightarrow sub \rightarrow pass \rightarrow sub \rightarrow fail \rightarrow STOP \\ T_T(\langle add, add, sub, add \rangle, add) &= \\ &inc \rightarrow add \rightarrow inc \rightarrow add \rightarrow inc \rightarrow sub \rightarrow inc \rightarrow add \rightarrow pass \rightarrow add \rightarrow fail \rightarrow STOP \\ T_T(\langle add, add, sub, sub \rangle, sub) &= \dots \\ &\dots \end{aligned}$$

This is, of course, an infinite set since the set $traces(Counter_2)$ is.

The next theorem establishes that an *SUT* that does not fail any of the tests in $Exhaust_T(SP)$ is a traces refinement of *SP*. Its proof uses Lemma 1 which is stated and proved in the appendix.

Theorem 2 (Exhaustivity of $Exhaust_T$). *Given two CSP processes, SUT and SP, $SP \sqsubseteq_T SUT$ if, and only if*

$$\forall T_T(s, a) : Exhaust_T(SP); t : traces(Execution_{SUT}^{SP}(T_T(s, a))) \bullet last(t) \neq fail$$

Proof

$$\forall T_T(s, a) : Exhaust_T(SP); t : traces(Execution_{SUT}^{SP}(T_T(s, a))) \bullet last(t) \neq fail$$

$$\Leftrightarrow \forall s, a, t \bullet \left(s \in traces(SP) \wedge a \notin initials(SP/s) \wedge t \in traces((SUT \llbracket \alpha SP \rrbracket T_T(s, a)) \setminus \alpha SP) \right) \Rightarrow last(t) \neq fail$$

[definition of $Exhaust_T(SP)$ and $Execution_{SUT}^{SP}(T_T(s, a))$]

$$\Leftrightarrow \forall s, a, t \bullet \left(s \in traces(SP) \wedge \langle a \rangle \notin traces(SP/s) \wedge t \in traces((SUT \llbracket \alpha SP \rrbracket T_T(s, a)) \setminus \alpha SP) \right) \Rightarrow last(t) \neq fail$$

[definition of *initials*]

$$\Leftrightarrow \forall s, a, t \bullet \left(s \in \text{traces}(SP) \wedge s \hat{\ } \langle a \rangle \notin \text{traces}(SP) \wedge \right. \\ \left. t \in \text{traces}((SUT \parallel [\alpha SP]) T_T(s, a)) \setminus \alpha SP \right) \Rightarrow \text{last}(t) \neq \text{fail}$$

[definition of $\text{traces}(SP/s)$ [23, page 48]]

$$\Leftrightarrow \forall s, a, t \bullet \left(s \notin \text{traces}(SP) \vee s \hat{\ } \langle a \rangle \in \text{traces}(SP) \vee \right. \\ \left. t \notin \text{traces}((SUT \parallel [\alpha SP]) T_T(s, a)) \setminus \alpha SP \vee \text{last}(t) \neq \text{fail} \right)$$

[propositional calculus]

$$\Leftrightarrow \forall \begin{pmatrix} s, \\ a, \\ t \end{pmatrix} \bullet \left(s \in \text{traces}(SP) \wedge \right. \\ \left. t \in \text{traces}((SUT \parallel [\alpha SP]) T_T(s, a)) \setminus \alpha SP \wedge \right. \\ \left. \text{last}(t) = \text{fail} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP)$$

[propositional calculus]

$$\Leftrightarrow \forall \begin{pmatrix} s, \\ a, \\ t \end{pmatrix} \bullet \left(s \in \text{traces}(SP) \wedge \right. \\ \left. \exists t_1, t_2 \bullet \left(t_1 \in \text{traces}(SUT) \wedge \right. \right. \\ \left. \left. t_2 \in \text{traces}(T_T(s, a)) \wedge \right. \right. \\ \left. \left. t \in (t_1 \parallel [\alpha SP] t_2) \downarrow \alpha SP \right) \wedge \right. \\ \left. \text{last}(t) = \text{fail} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP)$$

[definition of traces for hiding and parallelism [23, pages 84,70]]

$$\Leftrightarrow \forall \begin{pmatrix} s, \\ a, \\ t \end{pmatrix} \bullet \left(s \in \text{traces}(SP) \wedge \right. \\ \left. \exists \begin{pmatrix} t_1, \\ t_2, \\ t_3 \end{pmatrix} \bullet \left(t_1 \in \text{traces}(SUT) \wedge \right. \right. \\ \left. \left. t_2 \leq t_3 \wedge \right. \right. \\ \left. \left. \#t_3 = \#s \times 2 + 3 \wedge \right. \right. \\ \left. \left. \forall i : 1 \dots \#s \times 2 \bullet \right. \right. \\ \left. \left. \left(\text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \right. \right. \\ \left. \left. \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \right) \wedge \right. \right. \\ \left. \left. t_3(\#s \times 2 + 1) = \text{pass} \wedge \right. \right. \\ \left. \left. t_3(\#s \times 2 + 2) = a \wedge \right. \right. \\ \left. \left. t_3(\#s \times 2 + 3) = \text{fail} \wedge \right. \right. \\ \left. \left. t \in (t_1 \parallel [\alpha SP] t_2) \downarrow \alpha SP \right) \wedge \right. \\ \left. \text{last}(t) = \text{fail} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP)$$

[definition of T_T and of traces for prefixing and $STOP$ [23, page 37]]

$$\Leftrightarrow \forall \begin{pmatrix} s, \\ a, \\ t \end{pmatrix} \bullet \left(s \in \text{traces}(SP) \wedge \right. \\ \left. \exists t_1, t_2 \bullet \left(t_1 \in \text{traces}(SUT) \wedge \right. \right. \\ \left. \left. \#t_2 = \#s \times 2 + 3 \wedge \right. \right. \\ \left. \left. \forall i : 1 \dots \#s \times 2 \bullet \right. \right. \\ \left. \left. \left(\text{odd}(i) \Rightarrow t_2(i) = \text{inc} \wedge \right. \right. \\ \left. \left. \text{even}(i) \Rightarrow t_2(i) = s(i \text{ div } 2) \right) \wedge \right. \right. \\ \left. \left. t_2(\#s \times 2 + 1) = \text{pass} \wedge \right. \right. \\ \left. \left. t_2(\#s \times 2 + 2) = a \wedge \right. \right. \\ \left. \left. t_2(\#s \times 2 + 3) = \text{fail} \wedge \right. \right. \\ \left. \left. t \in (t_1 \parallel [\alpha SP] t_2) \downarrow \alpha SP \right) \wedge \right. \\ \left. \text{last}(t) = \text{fail} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP)$$

[$\text{fail} \notin t_1 \wedge \text{fail} \notin t_2 \Rightarrow \text{fail} \notin (t_1 \parallel [\alpha SP] t_2) \downarrow \alpha SP \Rightarrow \text{last}(t) \neq \text{fail}$, so $t_2 = t_3$]

$$\Leftrightarrow \forall \begin{pmatrix} s, \\ a, \\ t \end{pmatrix} \bullet \left(\exists t_2 \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ s \hat{\ } \langle a \rangle \in \text{traces}(SUT) \wedge \\ \#t_2 = \#s \times 2 + 3 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_2(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_2(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_2(\#s \times 2 + 1) = \text{pass} \wedge \\ t_2(\#s \times 2 + 2) = a \wedge \\ t_2(\#s \times 2 + 3) = \text{fail} \wedge \\ t \in (s \hat{\ } \langle a \rangle \llbracket \alpha SP \rrbracket t_2) \downarrow \alpha SP \end{array} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP) \right)$$

$[last(t) = fail \text{ if, and only if, } t_1 = t_1 \upharpoonright \alpha SP = front(t_2) \upharpoonright \alpha SP = s \hat{\ } \langle a \rangle]$

$$\Leftrightarrow \forall s, a \bullet \left(\exists t, t_2 \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge s \hat{\ } \langle a \rangle \in \text{traces}(SUT) \wedge \\ \#t_2 = \#s \times 2 + 3 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_2(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_2(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_2(\#s \times 2 + 1) = \text{pass} \wedge \\ t_2(\#s \times 2 + 2) = a \wedge \\ t_2(\#s \times 2 + 3) = \text{fail} \wedge \\ t \in (s \hat{\ } \langle a \rangle \llbracket \alpha SP \rrbracket t_2) \downarrow \alpha SP \end{array} \right) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP) \right)$$

[predicate calculus]

$$\Leftrightarrow \forall s, a \bullet s \in \text{traces}(SP) \wedge s \hat{\ } \langle a \rangle \in \text{traces}(SUT) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP)$$

$[t_1 \upharpoonright \alpha SP = s \hat{\ } \langle a \rangle, \text{ so } (s \hat{\ } \langle a \rangle \llbracket \alpha SP \rrbracket t_2) \downarrow \alpha SP \neq \emptyset]$

$$\Leftrightarrow \forall t \bullet t \neq \langle \rangle \wedge t \in \text{traces}(SUT) \Rightarrow t \in \text{traces}(SP) \quad [\text{Lemma 1}]$$

$$\Leftrightarrow \forall t \bullet t \in \text{traces}(SUT) \Rightarrow t \in \text{traces}(SP)$$

$[\langle \rangle \in \text{traces}(SUT) \text{ and } \langle \rangle \in \text{traces}(SP)]$

$$\Leftrightarrow \text{traces}(SUT) \subseteq \text{traces}(SP) \quad [\text{property of sets}]$$

$$\Leftrightarrow SP \sqsubseteq_T SUT \quad [\text{definition of } \sqsubseteq_T]$$

□

As mentioned in Section 3, on the basis of this exhaustive test set, it is possible to design selection and optimisation strategies for getting finite test sets.

5.2 Testing against refusals

In this section we address the problem of testing whether an *SUT* behaves as a *CSP* process SUT_{CSP} that satisfies $SUT_{CSP} \text{ conf } SP$. The definition of *conf* requires us to check that, after performing one of their common traces, the

failures of SUT are failures of SP as well. For that we check that, after every trace s of SP , the SUT cannot refuse all events in a set A accepted by SP .

This is achieved by executing the test described by the CSP process corresponding to the trace s followed by an external choice among the events in A . Basically, a test execution proposes to the SUT the traces of the CSP process s ; $(\square a \in A \bullet a \rightarrow STOP)$ where $s \in traces(SP)$ and $(s, A) \notin failures(SP)$. The associated verdict of one execution of such a test is as follows.

- If the trace s , followed by a deadlock is observed, the test execution is said to be a *failure*.
- If a trace $s \frown a$, with $a \in A$ is observed the result of the test is said to be a *success*.
- If a strict prefix of s followed by a deadlock is observed, the test execution is said to be *inconclusive*; the trace s has not been executed by the SUT during this test execution.

Using the same events *inc*, *pass*, and *fail* that modelled the verdict of test executions concerned with traces refinement, we define the test for a trace $s = a_1, a_2, \dots, a_n$ of SP and a set A such that $(s, A) \notin failures(SP)$, or in other words, $A \notin Ref(SP, s)$ as follows.

$$T_F(s, A) = inc \rightarrow a_1 \rightarrow inc \rightarrow a_2 \rightarrow inc \dots a_n \rightarrow fail \rightarrow (\square a \in A \bullet a \rightarrow pass \rightarrow STOP)$$

It can be formally defined as follows.

$$\begin{aligned} T_F(\langle \rangle, A) &= fail \rightarrow (\square a \in A \bullet a \rightarrow pass \rightarrow STOP) \\ T_F(\langle a \rangle \frown s, A) &= inc \rightarrow a \rightarrow T_F(s, A) \end{aligned}$$

Termination is not a special case here: every set is refused after a trace ending by \checkmark . If s ends in \checkmark , then there is no A that does not belong to the failures of SP [23, page 192], and so we do not need to define $T(\langle \checkmark \rangle, A)$.

When the SUT is nondeterministic, the global verdict for several executions of the same test is just as before.

- If there is one execution with a failure verdict, the SUT does not pass the test.
- If for all the test executions the verdict is either success or inconclusive, the SUT passes the test.

However, it is not necessary to consider all these tests because as soon as $(s, A) \notin failures(SP)$, then we have that $\forall A' \supset A \bullet (s, A') \notin failures(SP)$. If a system passes the test for A , it will in principle pass the test for A' ; the only concern would be with nondeterminism. On the other hand, if a system fails the test for A , then it may pass the test for A' , which offers more choices to the system, but a problem has already been identified anyway.

Thus for each trace s , it is sufficient to consider a subset of the sets A' such that (s, A') are not in $failures(SP)$; namely we consider the set \mathcal{A}_s of sets A_1, \dots, A_m of events such that for all A_i , $(s, A_i) \notin failures(SP)$, and for

all $(s, A) \notin failures(SP)$ there is $A_i \in \mathcal{A}_s$ such that $A \supseteq A_i$. These are the minimal acceptance sets of SP . In the case of a deadlock, there is no A such that $(s, A) \notin failures(SP)$, and in this case \mathcal{A}_s is empty. Precisely, we propose the following exhaustive minimal test set for refusal containment.

$$Exhaust_{conf}(SP) = \{T_F(s, A) \mid s \in traces(SP) \wedge A \in \mathcal{A}_s\}$$

where $\mathcal{A}_s = \min_{\subseteq}(\{A \mid (s, A) \notin failures(SP)\})$. For a set \mathcal{S} of sets, we define $\min_{\subseteq}(\mathcal{S}) = \{S \mid S \in \mathcal{S} \wedge \neg \exists S' \bullet S' \in \mathcal{S} \wedge S' \subset S\}$.

For the process *Counter*₂, we have the following minimal acceptances.

For $\langle \rangle$, we have $\{add\}$
 For $\langle add \rangle$, we have $\{add\}, \{sub\}$
 For $\langle add, add \rangle$, we have $\{sub\}$
 For $\langle add, sub \rangle$, we have $\{add\}$
 For $\langle add, add, sub \rangle$, we have $\{add\}, \{sub\}$
 ...

Thus, we have the following tests in the exhaustive test set.

$T_F(\langle \rangle, \{add\}) = fail \rightarrow add \rightarrow pass \rightarrow STOP$
 $T_F(\langle add \rangle, \{add\}) = inc \rightarrow add \rightarrow fail \rightarrow add \rightarrow pass \rightarrow STOP$
 $T_F(\langle add \rangle, \{sub\}) = inc \rightarrow add \rightarrow fail \rightarrow sub \rightarrow pass \rightarrow STOP$
 $T_F(\langle add, add \rangle, \{sub\}) = inc \rightarrow add \rightarrow inc \rightarrow add \rightarrow fail \rightarrow sub \rightarrow pass \rightarrow STOP$
 $T_F(\langle add, sub \rangle, \{add\}) = inc \rightarrow add \rightarrow inc \rightarrow sub \rightarrow fail \rightarrow add \rightarrow pass \rightarrow STOP$
 $T_F(\langle add, add, sub \rangle, \{add\}) = inc \rightarrow add \rightarrow inc \rightarrow add \rightarrow inc \rightarrow sub \rightarrow fail \rightarrow add \rightarrow pass \rightarrow STOP$
 ...

We prove below that the exhaustive test set is enough to establish conformance: an *SUT* for which none of the test executions deadlock after a *fail* is in conformance with *SP* according to *conf*.

Theorem 3 (Exhaustivity of $Exhaust_{conf}$). *Given two CSP processes SUT and SP, ($SUT \text{ conf } SP$) if, and only if,*

$$\forall T_F(s, A) : Exhaust_{conf}(SP); (t, B) : failures(Execution_{SUT}^{SP}(T_F(s, A))) \bullet last(t) \neq fail \vee B \neq \{inc, pass, fail\}$$

Proof

$$\forall T_F(s, A) : Exhaust_{conf}(SP); (t, B) : failures(Execution_{SUT}^{SP}(T_F(s, A))) \bullet last(t) \neq fail \vee B \neq \{inc, pass, fail\}$$

$$\Leftrightarrow \forall s, A, t, B \bullet \left(\begin{array}{l} s \in traces(SP) \wedge \\ A \in \min_{\subseteq}(\{X \mid (s, X) \notin failures(SP)\}) \wedge \\ (t, B) \in failures((SUT \llbracket \alpha SP \rrbracket T_F(s, A)) \setminus \alpha SP) \end{array} \right) \Rightarrow \\ (last(t) \neq fail \vee B \neq \{inc, pass, fail\}) \\ [definitions\ of\ Exhaust_{conf}(SP)\ and\ Execution_{SUT}^{SP}(T_F(s, A))]$$

$$\Leftrightarrow \forall s, A, t, B \bullet \left(\begin{array}{l} s \notin \text{traces}(SP) \vee \\ A \notin \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \vee \\ (t, B) \notin \text{failures}((SUT \llbracket \alpha SP \rrbracket T_F(s, A)) \setminus \alpha SP) \vee \\ \text{last}(t) \neq \text{fail} \vee B \neq \{\text{inc}, \text{pass}, \text{fail}\} \end{array} \right)$$

[propositional calculus]

$$\Leftrightarrow \forall s, A, t, B \bullet \left(\begin{array}{l} s \notin \text{traces}(SP) \vee \\ A \notin \{X \mid (s, X) \notin \text{failures}(SP)\} \vee \\ (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \vee \\ (t, B) \notin \text{failures}((SUT \llbracket \alpha SP \rrbracket T_F(s, A)) \setminus \alpha SP) \vee \\ \text{last}(t) \neq \text{fail} \vee B \neq \{\text{inc}, \text{pass}, \text{fail}\} \end{array} \right)$$

[definition of $\min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\})$]

$$\Leftrightarrow \forall s, A, t, B \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ (t, B) \in \text{failures}((SUT \llbracket \alpha SP \rrbracket T_F(s, A)) \setminus \alpha SP) \wedge \\ \text{last}(t) = \text{fail} \wedge B = \{\text{inc}, \text{pass}, \text{fail}\} \end{array} \right) \Rightarrow$$

$$((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A))$$

[property of sets and propositional calculus]

$$\Leftrightarrow \forall \left(\begin{array}{l} s, \\ A, \\ t, \\ B \end{array} \right) \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ \exists t_1 \bullet \left(\begin{array}{l} t = t_1 \upharpoonright \alpha SP \wedge \\ (t_1, B \cup \alpha SP) \in \text{failures}((SUT \llbracket \alpha SP \rrbracket T_F(s, A))) \end{array} \right) \wedge \\ \text{last}(t) = \text{fail} \wedge B = \{\text{inc}, \text{pass}, \text{fail}\} \\ (s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \end{array} \right) \Rightarrow$$

[definition of *failures* for hiding [23, page 199], and
 $[(SUT \llbracket \alpha SP \rrbracket T_F(s, A)) \setminus \alpha SP$ is divergence free]

$$\Leftrightarrow \forall \left(\begin{array}{l} s, \\ A, \\ t, \\ B \end{array} \right) \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ \exists \left(\begin{array}{l} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\begin{array}{l} t = t_1 \upharpoonright \alpha SP \wedge \\ B \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ (t_2, B_2) \in \text{failures}(SUT) \wedge \\ (t_3, B_3) \in \text{failures}(T_F(s, A)) \wedge \\ t_1 \in (t_2 \llbracket \alpha SP \rrbracket t_3) \end{array} \right) \wedge \\ \text{last}(t) = \text{fail} \wedge B = \{\text{inc}, \text{pass}, \text{fail}\} \\ (s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \end{array} \right) \Rightarrow$$

[definition of *failures* for parallelism [23, page 199] and
 $[SUT \llbracket \alpha SP \rrbracket T_F(s, A)$ is divergence free]

$$\begin{aligned}
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\begin{array}{c} t = t_1 \downarrow \alpha SP \wedge \\ \{ inc, pass, fail \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ \exists t_2, t_3 \bullet \left(\begin{array}{c} (t_2, B_2) \in failures(SUT) \wedge \\ (t_3, B_3) \in failures(T_F(s, A)) \wedge \\ t_1 \in (t_2 \parallel \alpha SP \parallel t_3) \end{array} \right) \wedge \end{array} \right) \right) \wedge \Rightarrow \\
& \left(\begin{array}{c} last(t) = fail \\ ((s, A) \in failures(SP) \vee (\exists A' \bullet (s, A') \notin failures(SP) \wedge A' \subset A)) \end{array} \right) \\
& \text{[predicate calculus: one-point-rule]}
\end{aligned}$$

$$\begin{aligned}
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_2, \\ t_3, \\ t_4 \end{array} \right) \bullet \left(\begin{array}{c} s \in traces(SP) \wedge \\ t = t_1 \downarrow \alpha SP \wedge \\ \{ inc, pass, fail \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ \left(\begin{array}{c} (t_2, B_2) \in failures(SUT) \wedge \\ (t_3, B_3) \in failures(T_F(s, A)) \wedge \\ t_1 \in (t_2 \parallel \alpha SP \parallel t_3) \wedge \\ t_3 \leq t_4 \wedge \#t_4 = \#s \times 2 + 3 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{c} odd(i) \Rightarrow t_4(i) = inc \wedge \\ even(i) \Rightarrow t_4(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_4(\#s \times 2 + 1) = fail \wedge \\ t_4(\#s \times 2 + 2) \in A \wedge \\ t_4(\#s \times 2 + 3) = pass \end{array} \right) \wedge \end{array} \right) \right) \wedge \Rightarrow \\
& \left(\begin{array}{c} last(t) = fail \\ ((s, A) \in failures(SP) \vee (\exists A' \bullet (s, A') \notin failures(SP) \wedge A' \subset A)) \end{array} \right) \\
& \text{[definition of } T_F(s, A) \text{, and]} \\
& \text{[of } traces \text{ for prefixing, } STOP \text{ and external choice [23, page 37]]}
\end{aligned}$$

$$\begin{aligned}
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_2, \\ t_3 \end{array} \right) \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ t = t_1 \upharpoonright \alpha SP \wedge \\ \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ \left(\begin{array}{l} (t_2, B_2) \in \text{failures}(SUT) \wedge \\ (t_3, B_3) \in \text{failures}(T_F(s, A)) \wedge \\ t_1 \in (t_2 \llbracket \alpha SP \rrbracket t_3) \wedge \\ \#s \times 2 + 1 \leq \#t_3 \leq \#s \times 2 + 2 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \wedge \\ \#t_3 = \#s \times 2 + 2 \Rightarrow \\ t_3(\#s \times 2 + 2) \in A \end{array} \right) \wedge \\ \text{last}(t) = \text{fail} \end{array} \right) \wedge \Rightarrow \\
& \left((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \right) \\
& \quad [\text{last}(t) = \text{fail} \Rightarrow \text{last}(t_1 \upharpoonright \alpha SP) = \text{fail},] \\
& \quad [\text{so } t_1 \in (t_1 \llbracket \alpha SP \rrbracket t_3) \text{ and } t_2 \in \text{traces}(SUT) \Rightarrow \text{fail} \in \text{ran } t_3, \text{ and}] \\
& \quad [\text{last}(t_4) = \text{pass} \notin \alpha SP \Rightarrow t_3 \neq t_4]
\end{aligned}$$

$$\begin{aligned}
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_2, \\ t_3 \end{array} \right) \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ t = t_1 \upharpoonright \alpha SP \wedge \\ \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ \left(\begin{array}{l} (t_2, B_2) \in \text{failures}(SUT) \wedge \\ (t_3, B_3) \in \text{failures}(T_F(s, A)) \wedge \\ t_1 \in (t_2 \llbracket \alpha SP \rrbracket t_3) \wedge \\ \#t_3 = \#s \times 2 + 1 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \end{array} \right) \wedge \\ \text{last}(t) = \text{fail} \end{array} \right) \wedge \Rightarrow \\
& \left((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \right) \\
& \quad [\{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \text{ and}] \\
& \quad [B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \text{ imply}] \\
& \quad [\{ \text{inc}, \text{pass}, \text{fail} \} \subseteq B_2, B_3,] \\
& \quad [\text{so } (t_3, B_3) \in \text{failures}(T_F(s, A)) \text{ implies } \#t_3 = \#s \times 2 + 1,] \\
& \quad [\text{by the definitions of } T_F(s, A) \text{ and of } \text{failures} [23, \text{pages } 197\text{-}8]]
\end{aligned}$$

$$\begin{aligned}
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists t_3 \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ t = t_1 \upharpoonright \alpha SP \wedge \\ \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ (s, B_2) \in \text{failures}(SUT) \wedge \\ (t_3, B_3) \in \text{failures}(T_F(s, A)) \wedge \\ t_1 \in (s \llbracket \alpha SP \rrbracket t_3) \wedge \\ \#t_3 = \#s \times 2 + 1 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \end{array} \right) \wedge \right. \\
& \left. \left(\begin{array}{l} \text{last}(t) = \text{fail} \\ ((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A)) \end{array} \right) \right) \wedge \Rightarrow \\
& \quad [\text{last}(t) = \text{fail} \Rightarrow \text{last}(t_1 \upharpoonright \alpha SP) = \text{fail}, \text{ so } t_1 \in t_2 \llbracket \alpha SP \rrbracket t_3 \Rightarrow t_2 = s] \\
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists t_3 \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge \\ t = t_1 \upharpoonright \alpha SP \wedge \\ \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ (s, B_2) \in \text{failures}(SUT) \wedge \\ B_3 \subseteq (\alpha SP \setminus A) \cup \{ \text{inc}, \text{pass}, \text{fail} \} \wedge \\ t_1 \in (s \llbracket \alpha SP \rrbracket t_3) \wedge \\ \#t_3 = \#s \times 2 + 1 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \end{array} \right) \wedge \right. \\
& \left. \left(\begin{array}{l} \text{last}(t) = \text{fail} \\ ((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A)) \end{array} \right) \right) \wedge \Rightarrow \\
& \quad [\text{definitions of } T_F(s, A) \text{ and } \text{failures} \text{ for external choice}] \\
& \Leftrightarrow \forall \left(\begin{array}{c} s, \\ A, \\ t \end{array} \right) \bullet \left(\exists \left(\begin{array}{c} t_1, \\ B_2, \\ B_3 \end{array} \right) \bullet \left(\exists t_3 \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge (s, A) \in \text{failures}(SUT) \wedge \\ t = t_1 \upharpoonright \alpha SP \wedge \\ \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ (s, B_2) \in \text{failures}(SUT) \wedge \\ B_3 \subseteq (\alpha SP \setminus A) \cup \{ \text{inc}, \text{pass}, \text{fail} \} \wedge \\ t_1 \in (s \llbracket \alpha SP \rrbracket t_3) \wedge \#t_3 = \#s \times 2 + 1 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \end{array} \right) \wedge \right. \\
& \left. \left(\begin{array}{l} \text{last}(t) = \text{fail} \\ ((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A)) \end{array} \right) \right) \wedge \Rightarrow \\
& \quad [B_3 \subseteq (\alpha SP \setminus A) \cup \{ \text{inc}, \text{pass}, \text{fail} \} \Rightarrow A \subseteq B_2 \Rightarrow (s, A) \in \text{failures}(SUT)]
\end{aligned}$$

$$\begin{aligned}
& \Leftrightarrow \forall s, A \bullet \left(\begin{array}{l} s \in \text{traces}(SP) \wedge (s, A) \in \text{failures}(SUT) \wedge \\ \exists t_1, t_3 \bullet \left(\begin{array}{l} t_1 \in (s \llbracket \alpha SP \rrbracket t_3) \wedge \\ \#t_3 = \#s \times 2 + 1 \wedge \\ \forall i : 1 \dots \#s \times 2 \bullet \\ \left(\begin{array}{l} \text{odd}(i) \Rightarrow t_3(i) = \text{inc} \wedge \\ \text{even}(i) \Rightarrow t_3(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ t_3(\#s \times 2 + 1) = \text{fail} \end{array} \right) \wedge \\ \exists B_2, B_3 \bullet \left(\begin{array}{l} \{ \text{inc}, \text{pass}, \text{fail} \} \cup \alpha SP = B_2 \cup B_3 \wedge \\ B_2 \setminus (\alpha SP \cup \{\checkmark\}) = B_3 \setminus (\alpha SP \cup \{\checkmark\}) \wedge \\ (s, B_2) \in \text{failures}(SUT) \\ B_3 \subseteq \alpha SP \setminus A \cup \{ \text{inc}, \text{pass}, \text{fail} \} \wedge \end{array} \right) \end{array} \right) \Rightarrow \\
& \quad \left((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \right) \\
& \quad \text{[one-point rule, } t_1 \in (s \llbracket \alpha SP \rrbracket t_3) \Rightarrow \text{last}(t_1 \downarrow \alpha SP) = \text{fail}] \\
& \Leftrightarrow \forall s, A \bullet s \in \text{traces}(SP) \wedge (s, A) \in \text{failures}(SUT) \Rightarrow \\
& \quad \left((s, A) \in \text{failures}(SP) \vee (\exists A' \bullet (s, A') \notin \text{failures}(SP) \wedge A' \subset A) \right) \\
& \quad [s \llbracket \alpha SP \rrbracket t_3 \neq \emptyset, (s, B_2 = A) \in \text{failures}(SUT), \text{ and}] \\
& \quad [B_3 = \alpha SP \setminus A \cup \{ \text{inc}, \text{pass}, \text{fail} \}] \\
& \Leftrightarrow \forall s, A \bullet s \in \text{traces}(SP) \wedge s \in \text{traces}(SUT) \wedge (s, A) \in \text{failures}(SUT) \Rightarrow \\
& \quad A \notin \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \\
& \quad \text{[definition of } \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\})] \\
& \Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
& \quad A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT) \\
& \quad [(s, A) \in \text{failures}(SUT) \Rightarrow s \in \text{traces}(SUT)] \\
& \Leftrightarrow \left(\begin{array}{l} \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\ A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT) \end{array} \right) \wedge \\
& \quad \left(\begin{array}{l} \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\ \left((s, A) \notin \text{failures}(SP) \wedge \right. \\ \left. (\exists A' \bullet (s, A') \notin \text{failures}(SUT) \wedge A' \subseteq A) \right) \Rightarrow (s, A) \notin \text{failures}(SUT) \end{array} \right) \\
& \quad \text{[failures}(SUT) \text{ is downward closed]} \\
& \Leftrightarrow \left(\begin{array}{l} \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\ A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT) \end{array} \right) \wedge \\
& \quad \left(\begin{array}{l} \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\ \left((s, A) \notin \text{failures}(SP) \wedge \right. \\ \left. (\exists A' \bullet A' \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \wedge A' \subseteq A) \right) \Rightarrow \\ (s, A) \notin \text{failures}(SUT) \end{array} \right) \\
& \quad \text{[(s, A) \notin failures}(SP) \text{ implies}] \\
& \quad [\exists A' \bullet A' \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \wedge A' \subseteq A, \text{ and}] \\
& \quad [A' \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT)]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
&\quad (A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT)) \wedge \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. (\exists A' \bullet A' \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \wedge A' \subseteq A) \right) \Rightarrow \\
&\quad (s, A) \notin \text{failures}(SUT) \\
&\hspace{15em} [\text{predicate calculus}]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
&\quad (A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT)) \wedge \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \left(\exists A' \bullet \left(\begin{array}{l} (s, A') \notin \text{failures}(SP) \wedge \\ \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A') \wedge \\ A' \subseteq A \end{array} \right) \right) \right) \Rightarrow \\
&\quad (s, A) \notin \text{failures}(SUT) \\
&\hspace{15em} [\text{definition of } \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\})]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
&\quad (A \in \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\}) \Rightarrow (s, A) \notin \text{failures}(SUT)) \wedge \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \left(\exists A' \bullet \left(\begin{array}{l} (s, A') \notin \text{failures}(SP) \wedge \\ \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A') \wedge \\ A' \subset A \end{array} \right) \right) \right) \Rightarrow \\
&\quad (s, A) \notin \text{failures}(SUT) \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A) \right) \Rightarrow (s, A) \notin \text{failures}(SUT) \\
&\hspace{15em} [A' \subseteq A \Leftrightarrow A' \subset A \vee A' = A \text{ and predicate calculus}]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \left(\exists A' \bullet \left(\begin{array}{l} (s, A') \notin \text{failures}(SP) \wedge \\ \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A') \wedge \\ A' \subset A \end{array} \right) \right) \right) \Rightarrow \\
&\quad (s, A) \notin \text{failures}(SUT) \wedge \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A) \right) \Rightarrow (s, A) \notin \text{failures}(SUT) \\
&\hspace{15em} [\text{definition of } \min_{\subseteq}(\{X \mid (s, X) \notin \text{failures}(SP)\})]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A) \right) \Rightarrow (s, A) \notin \text{failures}(SUT) \wedge \\
&\quad \left((s, A) \notin \text{failures}(SP) \wedge \right. \\
&\quad \left. \neg (\exists A'' \bullet (s, A'') \notin \text{failures}(SP) \wedge A'' \subset A) \right) \Rightarrow (s, A) \notin \text{failures}(SUT) \\
&\hspace{15em} [\text{property of sets: } \exists \mathcal{S} \bullet P(\mathcal{S}) \Leftrightarrow (\exists \mathcal{S} \bullet P(\mathcal{S}) \wedge \neg \exists \mathcal{S}' \bullet P(\mathcal{S}') \wedge \mathcal{S}' \subseteq \mathcal{S})]
\end{aligned}$$

$$\begin{aligned}
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet && \text{[propositional calculus]} \\
&\quad (s, A) \notin \text{failures}(SP) \Rightarrow (s, A) \notin \text{failures}(SUT) \\
&\Leftrightarrow \forall s, A \mid s \in \text{traces}(SP) \cap \text{traces}(SUT) \bullet && \text{[propositional calculus]} \\
&\quad (s, A) \in \text{failures}(SUT) \Rightarrow (s, A) \in \text{failures}(SP) \\
&\Leftrightarrow SUT \text{ conf } SP && \text{[definition of conf]} \\
&\square
\end{aligned}$$

Remark 5. This theorem is similar, up to the notation, to Proposition 4.5, proved by Tretmans in [27, page 85]. The main difference there is that $\text{initials}(SP/s)$ was added to the minimal set of acceptance sets for technical reasons: the test set was defined by induction, starting from the empty trace, and all the successors of the state before the last one must appear at each induction step in order to get all the traces at the next step.

There is also a similar result by Peleska and Siegel in [21], with a rather different formulation of the sets of acceptance sets to be considered. In their theoretical work, deadlock observations are characterised in terms of maximal traces. This is not accurate for nondeterministic systems, since in the traces model a prefix of a maximal trace may be included just because it is a prefix of a possible trace, or because the system may deadlock after that prefix. It is well known that the traces model is not enough to characterise failures. In practice, one uses timeout to conclude that there is a deadlock, but in the theoretical work, this must be expressed in terms of the failures model. In the test derivation method that has been applied to several industrial systems [22], though, Peleska and Siegel handle deadlock adequately.

5.3 Running tests against systems

The two last theorems are about CSP processes, namely a specification SP , an unknown process SUT_{CSP} such that the system under test behaves like it, and some tests. They state some equivalence between, on the one hand, a conformance relation between SP and SUT_{CSP} , and, on the other hand, some properties of the traces of the parallel composition of SUT_{CSP} with the tests. These theorems are fundamental for stating practical properties on testing the SUT .

In practice, for every test in Exhaust_T and $\text{Exhaust}_{\text{conf}}$, it is trivial to obtain some tester program (in any suitable language for interacting with the SUT , for instance TTCN, Concert C, ...), that behaves like the CSP test. When performing one test experiment of the SUT with the tester program corresponding to a test t , we define that $SUT \text{ passes}_1 t$ if the verdict as defined the previous section is not a failure. Now, from the second testability hypothesis, for any test t , there is an integer k that prescribes the number of experiments that must be performed with t . We define that $SUT \text{ passes } t$ if there is no failure observed when performing k experiments with t . We also define that $SUT \text{ passes } TS$ when SUT passes all the tests in a test set TS .

Theorem 2 above allows to say that, under the testability hypotheses, an *SUT* passes all the tests of $Exhaust_T(SP)$ if and only if $SP \sqsubseteq_T SUT_{CSP}$. In a more mathematical form we have:

$$Testability\ Hypotheses \implies (SUT\ passes\ Exhaust_T(SP) \Leftrightarrow SP \sqsubseteq_T SUT_{CSP})$$

Similarly, Theorem 3 and Theorem 1 allow us to say that under the testability hypotheses, an *SUT* passes all the tests of $Exhaust_T(SP)$ and $Exhaust_{conf}(SP)$ if, and only if, $SP \sqsubseteq_F SUT_{CSP}$.

$$Testability\ Hypotheses \implies \\ (SUT\ passes\ Exhaust_T(SP) \cup Exhaust_{conf}(SP) \Leftrightarrow SP \sqsubseteq_F SUT_{CSP})$$

Of course the set of experiments described above, that is, the *SUT* passing an exhaustive test set, is not realistic since the test sets are infinite. This leads to the problem of selecting a finite subsets of these experiments. This can be done by enriching the hypotheses on the *SUT* with so-called selection hypotheses, keeping the same kind of properties as above: under the testability hypotheses and the selection hypotheses, the *SUT* passes the selected test set if and only if it is a refinement of *SP*. Some hints on test selection are given later in Section 7.

6 Factorisation

In this section we discuss the issue of expressing the test sets in a more compact, factorised, way. We first consider the case of traces refinement.

The tests in $Exhaust_T$ can be factorised, taking advantage of the fact that the set of traces of a process is prefix-closed. This factorisation decreases the number of inconclusive executions, although it may result in some adaptive tests, originally called adaptive checking sequences [16]. They were introduced for dealing with a nondeterministic *SUT*. Instead of submitting a preset sequence of events to the *SUT*, a tree of possible behaviours is submitted to it, allowing a test to follow and reveal the nondeterministic choices of the *SUT*.

In the case of traces refinement testing, for a trace s , we define a factorised test $Fact_T^{SP}(s)$ which, after each of the events of s proposes to the *SUT* an external choice between

- the continuation of the trace and
- those events forbidden after the prefix of the trace executed so far.

It is formally defined as follows, in terms of the function $Fact_{tr}^{SP}(s, dt)$ that takes as an extra parameter the trace dt that has already been executed.

$$\begin{aligned} Fact_T^{SP}(s) &= Fact_{tr}^{SP}(s, \langle \rangle) \\ Fact_{tr}^{SP}(\langle \rangle, dt) &= TFail^{SP}(dt) \\ Fact_{tr}^{SP}(\langle a \rangle \frown s, dt) &= TFail^{SP}(dt) \sqcap inc \rightarrow a \rightarrow Fact_{tr}^{SP}(s, dt \frown \langle a \rangle) \\ TFail^{SP}(s) &= pass \rightarrow \sqcap a^f \notin initials(SP/s) \bullet a^f \rightarrow \overline{fail \rightarrow STOP}, \\ &\quad \text{provided } initials(SP/s) \neq \emptyset \\ TFail^{SP}(s) &= STOP, \text{ otherwise} \end{aligned}$$

The function $TFail^{SP}(s)$ defines the CSP process that proposes all the invalid

extensions of s according to SP .

For $Counter_2$, we have that $Fact_T^C(\langle add, add, sub, add \rangle)$ is the following test.

$pass \rightarrow sub \rightarrow fail \rightarrow STOP$

□

$inc \rightarrow add \rightarrow inc \rightarrow add \rightarrow \left(\begin{array}{l} pass \rightarrow add \rightarrow fail \rightarrow STOP \\ \square \\ inc \rightarrow sub \rightarrow inc \rightarrow add \rightarrow pass \rightarrow add \rightarrow fail \rightarrow STOP \end{array} \right)$

This factorised test subsumes three tests in the set $Exhaust_T(Counter_2)$, namely, $T_T(\langle \rangle, sub)$, $T_T(\langle add, add \rangle, add)$, and $T_T(\langle add, add, sub, add \rangle, add)$.

The factorised tests, however, have a problem concerning coverage of behaviours, since the choices are no more under the control of the test and can be biased. For example, in the above factorised test, after the SUT performs the trace $\langle add, add \rangle$, there is a choice between the testing events $pass$ and inc that is left up not to the test, but to the environment of the test execution. It is an external choice over events that are not in the alphabet of the SUT .

For the non-factorised tests, the environment of a test execution can be a simple process that is prepared to accept interaction on any of the events inc , $pass$, and $fail$, at any moment. Even in such a liberal environment, it is guaranteed that the interaction with the SUT defined by the trace that corresponds to the test is attempted in the test execution.

If the test is factorised, though, the environment of the test execution is offered choices between $pass$ and inc events, whenever there is a possibility, according to the specification, of extending the trace or deadlocking. To ensure coverage, both choices should be tried; in a simple environment like that described above, there is no such guarantee, and more care is needed in its design.

A related concern arises when there are several possibilities of failure. By way of illustration, we consider that the alphabet of $Counter_2$ includes a third event $mult$, which is always refused; the definition of $Counter_2$ remains that presented in Section 2. In this case, the factorised test takes the following shape.

$pass \rightarrow ((sub \rightarrow fail \rightarrow STOP) \square (mult \rightarrow fail \rightarrow STOP))$

□

$inc \rightarrow add \rightarrow \dots$

In this case, in the beginning, if the environment of the test execution chooses to synchronise on $pass$, it then has no control over the choice between sub and $mult$: these events are not in its alphabet. The test is not making a choice, but rather offering it to the SUT . If the SUT can perform any of them, the mistake is going to be detected, but it is not possible to determine which of the mistaken events are possible, since the SUT is not forced to perform any of them.

If the SUT can perform one of the mistaken events, the test execution will indicate a $fail$, but it will not be clear which of the choices was made; it is a choice internal to the test execution. If the SUT can perform both sub and $mult$ due to an internal nondeterminism, the second testability hypothesis guarantees that, after running the factorised test a certain number of times, both nondeterministic

choices will be made, but again the test executions will not indicate when this has happened. If the *SUT* offers *sub* and *mult* in an external choice, in the test execution, the choice becomes nondeterministic, and even though the testability hypothesis guarantees that all choices will be made, there is no way, again, of identifying the reason of the problems that will be indicated.

On the other hand, if the non-factorised tests $pass \rightarrow sub \rightarrow fail \rightarrow STOP$ and $pass \rightarrow mult \rightarrow fail \rightarrow STOP$ are used instead, given the testability hypothesis, the verdict is more precise. If only one of the mistaken events can be performed by the *SUT*, only the test that offers that event will signal a *fail*. If the *SUT* can perform both *sub* and *mult* due to an internal nondeterminism, then the testability hypothesis guarantees that, after running each test a certain number of times, the nondeterministic behaviour will be revealed. Therefore, the executions for both tests will reveal a failure, and it will be observed that both mistakes are possible. If, on the other hand, the *SUT* can perform both *sub* and *mult* due to an external choice, then the individual non-factorised tests will make the choice and reveal the individual problems straightaway.

An even more factorised test can be defined. The automaton that defines set of traces of the so-called *canonical tester* [3] can be visualised as the tree formed by the traces of *SP* decorated at each node by a choice between the forbidden events after the traces from the root to the node. Such events lead to a failure verdict followed by *STOP*. In this case, there is no need for an inconclusive verdict, but the problem of coverage discussed above arises also with valid continuations of the trace.

For example, the canonical tester for *Counter₂* takes the following shape.

$$pass \rightarrow \left(\begin{array}{l} sub \rightarrow fail \rightarrow STOP \\ \square \\ mult \rightarrow fail \rightarrow STOP \\ add \rightarrow \left(\begin{array}{l} add \rightarrow \dots \\ \square \\ sub \rightarrow \dots \\ \square \\ mult \rightarrow fail \rightarrow STOP \end{array} \right) \end{array} \right)$$

In this case, not only the environment cannot control the initial choice of mistaken events that are to be tried, that is, the choice between *sub* and *mult*, but it also cannot control whether the initial valid traces to be attempted are $\langle add, add \rangle$ or $\langle add, sub \rangle$, for example.

For this reason, the factorisation that we propose above is not the canonical tester. It provides some optimisation, in that it joins all the tests based on traces that are associated by the prefix relation, but it does not joint all the tests.

The test $Fact_T^{SP}(s)$ can replace in $Exhaust_T(SP)$ all the tests $T_T(s', a)$ such that s' is a prefix of s . Since the set of traces is infinite, we cannot trivially use $Fact_T^{SP}(s)$ to define an exhaustive test set which includes $Fact_T^{SP}(s)$ instead of the tests $T_T(s, a)$ for every every maximal trace s and its prefixes. The set of maximal traces is not well defined. Instead, $Fact_T^{SP}(s)$ can be used in conjunction

with selection of a subset of tests from $Exhaust_T(SP)$. For example, if we restrict the size of the traces that are checked, we can define the set of maximal traces, and use $Fact_T^{SP}(s)$ to significantly diminish the number of tests of interest.

This is justified by the theorem below, which states that the failures uncovered by running the factorised test are the same as those discovered by running the corresponding tests of $Exhaust_T$.

Theorem 4 (Validity of factorisation). *For every $s \in traces(SP)$,*

$$traces(Execution_{SUT}^{SP}(Fact_T^{SP}(s))) = \bigcup \{ traces(Execution_{SUT}^{SP}(T_T(s', a))) \mid T_T(s', a) \in Exhaust_T(SP) \wedge s' \leq s \}$$

Proof

$$\begin{aligned} & traces(Execution_{SUT}^{SP}(Fact_T^{SP}(s))) \\ &= traces((SUT \parallel \alpha SP) \parallel Fact_T^{SP}(s)) \alpha SP \quad [\text{definition of } Execution_{SUT}^{SP}(Fact_T^{SP}(s))] \\ &= \left\{ t \downarrow \alpha SP \mid \exists u, v \bullet \left(u \in traces(SUT) \wedge v \in traces(Fact_T^{SP}(s)) \wedge \right. \right. \\ & \quad \left. \left. t \in (u \parallel \alpha SP) \parallel v \right) \right\} \quad [\text{definitions of } traces \text{ for hiding [23, page 84] and parallelism [23, page 70]}] \\ &= \left\{ t \downarrow \alpha SP \mid \exists u, v \bullet \left(\exists w \bullet \left(\begin{array}{l} u \in traces(SUT) \wedge \\ v \leq w \wedge \#w \leq \#s + 3 \wedge \\ \forall i : 1.. \#w - 3 \bullet \left(\begin{array}{l} odd(i) \Rightarrow w(i) = inc \wedge \\ even(i) \Rightarrow w(i) = s(i \text{ div } 2) \end{array} \right) \wedge \\ w(\#w - 2) = pass \wedge \\ w(\#w - 1) \notin initials(SP / ((1..(\#w - 3) \text{ div } 2) \triangleleft s)) \wedge \\ w(\#w) = fail \end{array} \right) \wedge \right. \right. \\ & \quad \left. \left. t \in (u \parallel \alpha SP) \parallel v \right) \right) \right\} \quad [\text{definitions of } Fact_T^{SP}(s) \text{ and } traces \text{ [23, page 37]}] \\ &= \left\{ t \downarrow \alpha SP \mid \exists u, v \bullet \left(\exists w, s', a \bullet \left(\begin{array}{l} u \in traces(SUT) \wedge \\ s' \leq s \wedge a \notin initials(SP / s') \wedge \\ v \leq w \wedge \#w = \#s' + 3 \wedge \\ \forall i : 1.. \#s' \times 2 \bullet \left(\begin{array}{l} odd(i) \Rightarrow w(i) = inc \wedge \\ even(i) \Rightarrow w(i) = s'(i \text{ div } 2) \end{array} \right) \wedge \\ w(\#s' \times 2 + 1) = pass \wedge \\ w(\#s' \times 2 + 2) = a \\ w(\#s' \times 2 + 3) = fail \end{array} \right) \wedge \right. \right. \\ & \quad \left. \left. t \in (u \parallel \alpha SP) \parallel v \right) \right) \right\} \quad [\text{property of sequences}] \end{aligned}$$

$$\begin{aligned}
& = \left\{ \left(t \downarrow \alpha SP \mid \left(\exists s', a \bullet \left(\exists u, v \bullet \left(\exists w \bullet \left(\begin{aligned} & u \in \text{traces}(SUT) \wedge \\ & v \leq w \wedge \#w = \#s' + 3 \wedge \\ & \forall i:1.. \#s' \times 2 \bullet \left(\begin{aligned} & \text{odd}(i) \Rightarrow w(i) = inc \wedge \\ & \text{even}(i) \Rightarrow w(i) = s'(i \text{ div } 2) \end{aligned} \right) \right) \wedge \\ & w(\#s' \times 2 + 1) = pass \wedge \\ & w(\#s' \times 2 + 2) = a \\ & w(\#s' \times 2 + 3) = fail \\ & t \in (u \llbracket \alpha SP \rrbracket v) \end{aligned} \right) \right) \right) \mid \left. \begin{aligned} & s' \leq s \wedge a \notin \text{initials}(SP/s') \end{aligned} \right\} \right) \right\} \\
& \hspace{15em} [\text{predicate calculus}] \\
& = \left\{ \left(t \downarrow \alpha SP \mid \left(\exists s', a \bullet \left(\exists u, v \bullet \left(u \in \text{traces}(SUT) \wedge v \in \text{traces}(T_T(s', a)) \wedge \right) \right) \right) \mid \left(t \in (u \llbracket \alpha SP \rrbracket v) \right) \right) \right\} \\
& \hspace{15em} [\text{definition of } T_T(s', a) \text{ and } \text{traces} [23, \text{page } 37]] \\
& = \bigcup \left\{ \left\{ \left(t \downarrow \alpha SP \mid \left(\exists u, v \bullet \left(u \in \text{traces}(SUT) \wedge v \in \text{traces}(T_T(s', a)) \wedge \right) \right) \right) \mid \left(t \in (u \llbracket \alpha SP \rrbracket v) \right) \right\} \mid \left(s' \leq s \wedge s' \in \text{traces}(SP) \wedge a \notin \text{initials}(SP/s') \right) \right\} \\
& \hspace{15em} [\text{property of sets and } s' \leq s \wedge s \in \text{traces}(SP) \Rightarrow s' \in \text{traces}(SP)] \\
& = \bigcup \left\{ \left(\text{traces}((SUT \llbracket \alpha SP \rrbracket T_T(s', a)) \setminus \alpha SP) \mid \left(s' \leq s \wedge s' \in \text{traces}(SP) \wedge a \notin \text{initials}(SP/s') \right) \right) \right\} \\
& \hspace{15em} [\text{definition of } \text{traces} \text{ for hiding [23, page 84] and parallelism [23, page 70]}] \\
& = \bigcup \{ \text{traces}(\text{Execution}_{SUT}^{SP}(T_T(s', a))) \mid T_T(s', a) \in \text{Exhaust}_T(SP) \wedge s' \leq s \} \\
& \hspace{15em} [\text{definitions of } \text{Execution}_{SUT}^{SP}(T_T(s', a)) \text{ and } \text{Exhaust}_T(SP)] \\
& \square
\end{aligned}$$

Several authors [3, 27, 21] have studied the minimisation and factorisation of the exhaustive test set for the *conf* relation. Brinksma in [3], and later on Tretmans in [27], provide some ways of building some canonical tester, that is, some nondeterministic tester process whose behaviour contains all the tests in $\text{Exhaust}_{\text{conf}}(SP)$. The factorisation is less obvious than for traces refinement since all acceptable sets must be attempted after a given trace. It leads to highly nondeterministic testers. In practice, this formulation raises issues of coverage of the test set, as discussed above for $\text{Exhaust}_T(SP)$.

7 Hints on Test Selection and Derivation

A testing strategy can be formalised as a way of selecting some finite subset of an exhaustive test set. The choice of such a strategy corresponds to stronger hypotheses on the system under test than the testability hypotheses discussed in

Section 4. Such hypotheses are called selection hypotheses in [1]. Weak selection hypotheses lead to large test sets. Strong selection hypotheses lead to smaller, more practicable test sets, with the risk that they may not be fulfilled.

Various selection hypotheses can be formulated and combined depending on some knowledge of the program, some coverage criteria of the specification and ultimately cost considerations. For instance, a *regularity hypothesis* uses a size function on the tests and has the form, for a given exhaustive test set: “if the subset of the exhaustive test set made up of all the tests of size less than or equal to a given limit is passed, then the exhaustive test set is as well”.

For $Exhaust_T$ and $Exhaust_{conf}$, an obvious candidate for a size function on tests such as $T_T(s, a)$ and $T_F(s, A)$ is the length of the trace s . Given the precise way in which these tests are specified in subsections 5.1 and 5.2, it is straightforward to implement test generators corresponding to these selection hypotheses. It must be noted, however, that regularity hypotheses are not always a good choice in practice. For instance, in [8], Dong and Frankl report cases where such a strategy failed to detect important faults.

A popular criterion for model-based testing (finite state machines or labelled transition systems) is transition coverage. The corresponding selection hypothesis is a so-called *uniformity hypothesis*. Such hypotheses are common in software testing. They assume that the system behaves uniformly on some test subsets. Thus it is enough to have only one test from each of these subsets.

In the case of transition coverage, it can be reworded, for a given exhaustive test set, as: “if a subset of the exhaustive test set that exercises all the transitions is passed, then the exhaustive test set is as well”. Given a finite model, it is quite feasible to develop a generator that yields a set of paths satisfying this criteria (see for instance [5, 16]). One justification of this selection hypothesis is that in model-based testing (based on finite state machines or labeled transition systems), there is a testability hypothesis similar to our first one: that the *SUT* behaves like a finite model. Since such models have no memory, the execution of a transition is independent of the way it has been reached, and it is sufficient to exercise it once, checking that the output (if any) is correct, and that the arrival state in the *SUT* is equivalent to the arrival state in the model.

The framework that we have developed so far for CSP-based testing is based on its denotational semantics. As mentioned in Section 4, to consider selection strategies based on states or transitions, we need to work with the finite labelled transition systems derived from CSP specifications using its operational semantics. A brute-force way of transposing transition coverage into our framework could be to select one subset of $Exhaust_T$ (resp., in $Exhaust_{conf}$), such that the set of the traces s that originate the selected $T_T(s, a)$ (resp., $T_F(s, A)$) ensures the coverage of all the transitions of this labelled transition system.

However, coverage of transitions is not just exercising the transitions, but, importantly, checking that the arrival state after each transition in the *SUT* is a right one: it accepts or refuses events that are compatible with the conformance relation. Here the conformance relations are derived from the notions of refinement, namely, $SP \sqsubseteq_T SUT_{CSP}$ and $SUT_{CSP} \text{ conf } SP$. These relations rely

on traces, as they appear in the form of the tests, in both cases. In our testing approach, these traces correspond to full paths from the initial state, and transitions are not considered individually. Thus it is not clear that transition coverage is an adequate selection criteria for the approach of CSP-based testing that is presented here. Starting from the exhaustive test sets we have defined, new uniformity hypotheses must be investigated in order to propose pertinent selection strategies. This is the subject of future work.

8 Inputs and outputs

So far, we have considered events, with no distinction between inputs and outputs. This distinction is extremely important in testing. The choice of inputs is under the control of the tester. The outputs are under the control of the *SUT* and provide the information for stating the verdict.

If we consider again our small *Replicator* example given in Section 2, for example, we observe that $Exhaust_T(Replicator)$ contains the following tests.

$$\begin{aligned}
T_T(\langle c.0 \rangle, c.1) &= inc \rightarrow c.0 \rightarrow pass \rightarrow c.1 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.0 \rangle, c.2) &= inc \rightarrow c.0 \rightarrow pass \rightarrow c.2 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.1 \rangle, c.0) &= inc \rightarrow c.1 \rightarrow pass \rightarrow c.0 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.1 \rangle, c.2) &= inc \rightarrow c.1 \rightarrow pass \rightarrow c.2 \rightarrow fail \rightarrow STOP \\
\dots & \\
T_T(\langle c.0, c.0, c.0 \rangle, c.1) &= \\
&\quad inc \rightarrow c.0 inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow pass \rightarrow c.1 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.0, c.0, c.0 \rangle, c.2) &= \\
&\quad inc \rightarrow c.0 inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow pass \rightarrow c.2 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.0, c.0, c.1 \rangle, c.0) &= \\
&\quad inc \rightarrow c.0 inc \rightarrow c.0 \rightarrow inc \rightarrow c.1 \rightarrow pass \rightarrow c.0 \rightarrow fail \rightarrow STOP \\
T_T(\langle c.0, c.0, c.1 \rangle, c.2) &= \\
&\quad inc \rightarrow c.0 inc \rightarrow c.0 \rightarrow inc \rightarrow c.1 \rightarrow pass \rightarrow c.2 \rightarrow fail \rightarrow STOP \\
\dots &
\end{aligned}$$

In $Exhaust_{conf}$, we have the following tests.

$$\begin{aligned}
T_F(\langle \rangle, \{ c.0 \}) &= fail \rightarrow c.0 \rightarrow pass \rightarrow STOP \\
T_F(\langle \rangle, \{ c.1 \}) &= fail \rightarrow c.1 \rightarrow pass \rightarrow STOP \\
T_F(\langle \rangle, \{ c.2 \}) &= fail \rightarrow c.2 \rightarrow pass \rightarrow STOP \\
T_F(\langle c.0 \rangle, \{ c.0 \}) &= inc \rightarrow c.0 \rightarrow fail \rightarrow c.0 \rightarrow pass \rightarrow STOP \\
\dots & \\
T_F(\langle c.0, c.0 \rangle, \{ c.1 \}) &= \\
&\quad inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow fail \rightarrow c.1 \rightarrow pass \rightarrow STOP \\
T_F(\langle c.0, c.0 \rangle, \{ c.2 \}) &= \\
&\quad inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow fail \rightarrow c.2 \rightarrow pass \rightarrow STOP \\
T_F(\langle c.0, c.0, c.0 \rangle, \{ c.0 \}) &= \\
&\quad inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow inc \rightarrow c.0 \rightarrow fail \rightarrow c.0 \rightarrow pass \rightarrow STOP \\
\dots &
\end{aligned}$$

We proved that these sets are enough to indicate mistaken implementations, but

this is under our first testability hypothesis: that the *SUT* can be accurately described as a CSP process. It raises an issue related to input and output that is not directly captured in CSP: that of origin of data communication.

As described in Section 2, in CSP, inputs and outputs are only syntactic sugar for synchronisations on events with composite names. For example, the process *BReplicator* defined below is not at all different from *Replicator* itself.

$$BReplicator = (c?x \rightarrow c!x \rightarrow BReplicator) \square (c!0 \rightarrow c!0 \rightarrow BReplicator)$$

We could say that it is a process that, instead of waiting for an input, may decide to output 0, twice. Its CSP model, however, is exactly as that of *Replicator*, since $c!0 \rightarrow c!0 \rightarrow Replicator$ is a choice already offered by the input.

If we are concerned with checking that an implementation does not decide to make progress without duly waiting for input from the environment, this CSP approach to modelling is not appropriate. In [23, page 302], Roscoe mentions the possibility of introducing the notion of input and output as a basic concept in CSP, by making outputs undelayable events, in much the same way that the termination event \checkmark is undelayable. Much of the work on this has been carried out in the context of security and timed applications.

In particular, Schneider [24] defines “may” and “must” tests in the context of a partition of events that classifies refusable and non-refusable event, but also high-level and low-level events, for the purposes of security applications. Schneider is interested in new conformance relations, rather than refinement, and on the use of model checking, rather than testing.

An interesting line for future work is the extension of CSP to include delayable and non-delayable events as suggested in [23], and analyse how results on testing based on input-output labelled transitions systems [28], and on other similar formalisms, can be cast in this new version of CSP.

By taking inputs and outputs into account, we are likely to be able to factorise some of the tests that are based on the several traces generated by the implicit choice associated with a CSP input. This may be helpful from a pragmatic point of view, as discussed in Section 6.

9 Conclusions

In this paper we have established a solid foundation for model-based testing using CSP. We have characterised the relevant testability hypotheses, and discussed their consequences. We have concentrated on testing for traces and failures refinement, but discussed the issues raised by divergence. We have proposed exhaustive test sets; the algebraic proofs of exhaustiveness are directly based on the definition of the semantics of CSP. We have considered some possible optimisations of our tests, with the observation, however, that optimisations raise issues of controllability. Finally, we have indicated the challenges imposed by inputs and outputs, and test selection based on labelled transition systems.

In [22], Peleska and Siegel present a pioneering work on CSP-based testing. They define and study two extra relations, divergence refinement and robustness.

However, they point out divergent specifications are not very useful, and it is not clear how they handle divergent implementations. Their test executions do not hide the events of the specification, and so they allow interference from the environment in the interaction between the test and the *SUT*. Their tests use only one extra event; it characterises success. In the absence of a success, they do not reveal if the test is inconclusive or a failure. They define may and must tests; we do not make this distinction because we are able to give an inconclusive verdict. Using the three events *pass*, *inc*, and *fail*, we have a very direct model of the verdict. Their definitions of tests are based on traces, but assume the possibility of infinite traces, as described in the operational semantics. For these, their tests are not well-defined CSP processes. Since we base our work on the denotational semantics, we have a natural characterisation of the set of finite traces that are relevant for a partial, but widely accepted characterisation of CSP processes: its canonical failures-divergences model.

The failures-divergences model that we adopt here is in direct correspondence with the UTP model of CSP processes. We expect to be able to recast our results in the UTP easily, and pave the way to consider more sophisticated concurrent languages that include constructs from other programming paradigms. In particular, we are interested in a combination of CSP and Z [25] that is adequate for refinement called *Circus* [20].

The next step in our work plans, however, is the characterisation of test selection and generation techniques. We plan to use the CSP model checker to provide some empirical results that will guide further work on *Circus*.

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A Lemma

Lemma 1. *For all processes SP and SUT ,*

$$(\forall s, a \bullet s \in \text{traces}(SP) \wedge s \hat{\ } \langle a \rangle \in \text{traces}(SUT) \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SP))$$

\Leftrightarrow

$$(\forall t \bullet t \neq \langle \rangle \wedge t \in \text{traces}(SUT) \Rightarrow t \in \text{traces}(SP))$$

Proof (\Rightarrow) By induction on t .

Base case: $\langle a \rangle$

$$\begin{aligned} & \langle a \rangle \in \text{traces}(SUT) \\ & = \langle \rangle \in \text{traces}(SP) \wedge \langle \rangle \hat{\ } \langle a \rangle \in \text{traces}(SUT) && [(\langle \rangle \in \text{traces}(SP) \text{ and } \langle a \rangle = \langle \rangle \hat{\ } \langle a \rangle)] \\ & \Rightarrow \langle \rangle \hat{\ } \langle a \rangle \in \text{traces}(SP) && [\text{assumption}] \\ & = \langle a \rangle \in \text{traces}(SUT) && [(\langle a \rangle = \langle \rangle \hat{\ } \langle a \rangle)] \end{aligned}$$

Inductive step: $s \hat{\ } \langle a \rangle$, with $s \neq \langle \rangle$

$$\begin{aligned} & s \hat{\ } \langle a \rangle \in \text{traces}(SUT) \\ & = s \in \text{traces}(SUT) \wedge s \hat{\ } \langle a \rangle \in \text{traces}(SUT) && [\text{traces}(SUT) \text{ is prefix closed}] \\ & \Rightarrow s \in \text{traces}(SP) \wedge s \hat{\ } \langle a \rangle \in \text{traces}(SP) && [\text{induction hypothesis}] \\ & \Rightarrow s \hat{\ } \langle a \rangle \in \text{traces}(SUT) && [\text{assumption}] \\ & \square \end{aligned}$$