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Formal mutation testing for Circus

Alex Alberto\textsuperscript{a}, Ana Cavalcanti\textsuperscript{b}, Marie-Claude Gaudel\textsuperscript{c}, Adenilso Simão\textsuperscript{a}

\textsuperscript{a}Universidade de São Paulo, ICMC, São Carlos, Brazil
\textsuperscript{b}University of York, Department of Computer Science, York YO10 5GH, UK
\textsuperscript{c}LRI, Université de Paris-Sud and CNRS, Orsay 91405, France

Abstract

Context: The demand from industry for more dependable and scalable test-development mechanisms has fostered the use of formal models to guide the generation of tests. Despite many advancements having been obtained with state-based models, such as Finite State Machines (FSMs) and Input/Output Transition Systems (IOTSs), more advanced formalisms are required to specify large, state-rich, concurrent systems. Circus, a state-rich process algebra combining Z, CSP and a refinement calculus, is suitable for this; however, deriving tests from such models is accordingly more challenging. Recently, a testing theory has been stated for Circus, allowing the verification of process refinement based on exhaustive test sets.

Objective: We investigate fault-based testing for refinement from Circus specifications using mutation. We seek the benefits of such techniques in test-set quality assertion and fault-based test-case selection. We target results relevant not only for Circus, but to any process algebra for refinement that combines CSP with a data language.

Method: We present a formal definition for fault-based test sets, extending the Circus testing theory, and an extensive study of mutation operators for Circus. Using these results, we propose an approach to generate tests to kill mutants. Finally, we explain how prototype tool support can be obtained with the implementation of a mutant generator, a translator from Circus to CSP, and a refinement checker for CSP, and with a more sophisticated chain of tools that support the use of symbolic tests.

Results: We formally characterise mutation testing for Circus, defining the exhaustive test sets that can kill a given mutant. We also provide a technique to select tests from these sets based on specification traces of the mutants. Finally, we present mutation operators that consider faults related to both reactive and data manipulation behaviour. Altogether, we define a new fault-based test-generation technique for Circus.

Conclusion: We conclude that mutation testing for Circus can truly aid making test generation from state-rich model more tractable, by focussing on particular faults.

Keywords: Circus, mutation, testing, formal specification

1. Introduction

Testing from formal models is currently advancing as a solid approach to support the growing demand from industry for more dependable and scalable test-development
mechanisms. For instance, Model-Based Testing (MBT) benefits greatly from a precise and clear semantics for models, as opposed to informal or semi-formal models whose semantics is dependent on the particular tool in use.

Many advancements have been obtained with state-based models, such as Finite State Machines (FSMs) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] and Input/Output Transition Systems (IOTSs) [11, 12, 13, 14, 15]. Those models, however, quickly become intractable when dealing with larger systems. Thus, more advanced formalisms are required to facilitate the specification of large, state-rich, concurrent systems.

*Circus* is a state-rich process algebra combining Z [16], CSP [17], and a refinement calculus [18]. Its denotational and operational semantics are based on the Unifying Theories of Programming (UTP) [19]. *Circus* can be used to verify large concurrent systems, including those that cannot be handled by model checking. *Circus* has already been used to verify, for example, software in aerospace applications [20], and novel virtualization software by the US Naval Research Laboratory [21].

A theory of testing for *Circus* [22], instantiating Gaudel’s long-standing theory of formal testing [23, 24, 25], is available. It is founded on the *Circus* operational semantics [26], described and justified in the UTP [27]. As usual in testing, it considers divergence-free processes for the model and the system under test. More precisely, if a system under test diverges, since one cannot decide whether it is deadlocked or divergent, divergence is assimilated to an unspecified deadlock and detected as a failure.

The *Circus* testing theory introduces potentially infinite (symbolic) exhaustive test sets. To achieve practical usefulness, it is, therefore, mandatory to rely on selection criteria both to generate and to select a finite set of tests.

Test-case generation in model-based testing is guided by testing requirements that should be met by a test suite. Usually, the requirements are either coverage criteria that state which elements of the model should be traversed (covered) by test execution, or fault models, which define specific faults that the test cases are supposed to reveal, if present in the system. These approaches are usually complementary to each other. Coverage-based testing is proposed for *Circus* in [28]. It is worth investigating how fault-based testing can complement the coverage testing.

Mutation testing is recognized as one of the most effective fault-detection techniques [29]. The systematic injection of feasible modeling faults into specifications allows the prediction of potential defective implementations. The faults are seeded by syntactic changes that may affect the observable specified behavior. Such faulty models are “mutants”. A mutant is “killed” by a test case able to expose its observable behavior difference. Testing can benefit from mutation in two ways [30]: some quality aspects of a test set can be measured by the number of mutants it can kill, and the analysis of a mutant model allows the selection of tests targeting specific faults or fault classes.

In this paper, we introduce an approach to apply mutation testing to *Circus* specifications. Most of the presented mutation operators, that is, the fault-injection strategies, are based on previous works that have tackled similar challenges in related modeling languages [31, 32, 33]. The outcome of all mutation operators are, however, analyzed considering the specific features and particularities of *Circus*. Moreover, our results are valid in the context of other process algebras, especially those based on CSP [34, 35].

The contribution of this paper is manifold. First, we instantiate the notions of mutation testing for a state-rich concurrent language, namely, *Circus*, and its formal
theory of testing. In particular, we face the challenge of associating mutations in the
text of a Circus specification to traces of the Circus denotational semantics that define
tests that cover the mutation. Even though mutation testing has already been applied to
languages and theories upon which Circus is based, such as CSP [31] and the UTP [36],
the consideration of a state-rich process algebra for refinement with a UTP semantics
is novel. Second, we propose mutation operators for Circus, analysing and adapting
existing ones for the underlying languages and designing some that are specific to
Circus. Third, we describe prototype tool support for the application of the mutant
operators and two approaches to generate tests that can kill these mutants. When it is
feasible to translate the considered Circus specification into CSP, we propose the use
of the FDR model checker. For the other cases, we identify a tool chain that copes
directly with Circus specifications via slicing techniques and symbolic execution.

This paper is organized as follows. Section 2 gives an overview of the aspects of
Circus and its testing theory that we use here. Section 3 extends the testing theory
to consider mutation testing and describes our approach to generating tests based on
mutants. The mutation operators used to generate the mutants themselves are defined
in Section 4. Tool support for automation of our approach is discussed in Section 5
and an extra complete example is introduced in Section 6. Finally, we present some
related and future work and conclusions in Sections 7 and 8.

2. Circus and its testing theory

In this section, we give a brief description of the Circus language, its operational
semantics [26], and its testing theory [22].

2.1. Circus notation and operational semantics

As exemplified is Figure 1, Circus allows us to model systems and their compo-
nents via (a network of) interacting processes. In Figure 1, we define a single process
Chrono that specifies the reactive behaviour of a chronometer. This is a process that
recognises tick events that mark the passage of time, a request to output the current
time via a channel time, and outputs minutes and seconds via a channel out.

A Circus specification is defined by a sequence of paragraphs. Roughly speaking,
they define processes, but also channels, and any types and functions used in the pro-
cess specifications. In Figure 1, we define a type RANGE, including the valid values
for seconds and minutes, and the channels tick, time and out. The channel out is
typed, since it is used to communicate the current minutes and seconds recorded in the
chronometer as a pair. The final paragraph in Figure 1 defines Chrono itself.

Each process has:

- **a state** and some operations for observing and changing it in a Z style. In Chrono, the
  state is composed by a pair AState of variables named sec and min with integer
  values between 0 and 59 (as defined by RANGE), and the data operations on
  this state are specified by the three schemas AInit, IncSec, IncMin.

- **actions** that define communicating behaviours in a CSP style. The overall behaviour of
  a process is specified by the main action after the symbol $\bullet$. In our example, it is a
Figure 1: A Circus specification of a chronometer

sequential composition of the schema AInit followed by the repeated execution of the Run action. The Circus construct $\mu X \cdot A(X)$ defines a recursive action $A$, in which $X$ is used for recursive calls.

The initialisation schema AInit defines the values sec' and min' of the state components after the initialisation. These components are declared using AState'. The operation schemas IncSec and IncMin change the state, as indicated by the declaration $\Delta AState$. They also define values sec' and min' of the state components after the operations. In each case, the seconds and minutes are incremented modulo 60.

Run starts with an external choice (□) between the events tick and time. If the environment chooses the event tick, this is followed by the increment of the chronometer using the data operation IncSec. Afterwards, we have another choice between actions guarded by the conditions sec = 0 and sec ≠ 0. If, after the increment, we have sec = 0, then the minutes are incremented using IncMin. Otherwise, the action terminates (Skip). If the event time occurs, then the values of min and sec are displayed (output), using the channel out, before termination.

Circus comes with a denotational and an operational semantics, based on Hoare and He’s Unifying Theories of Programming (UTP) [19], and a notion of refinement. We can use Circus to write abstract as well as more concrete specifications, or even programs. A full account of Circus and its denotational semantics is given in [37].

The operational semantics [26] plays an essential role on the definition of testing strategies based on Circus specifications. It is briefly introduced below, and a significant part is reproduced in Appendix A. It is defined as a symbolic labelled transition system between configurations. These are triples ($c \parallel s \parallel A$), with a constraint $c$, a state $s$, and a continuation $A$, which is a Circus action. Transitions associate two con-
figurations and a label. The labels are either empty, represented by \( \varepsilon \), or symbolic communications of the form \( c?w \) or \( c!w \), where \( c \) is a channel name and \( w \) is a symbolic variable that represents an input (?) or an output (!) value.

The first component \( c \) of a configuration \( (c \mid s \models A) \) is a constraint over symbolic variables that are used to define labels and the state. The constraints are texts that denote \textit{Circus} predicates over these symbolic variables. We use typewriter font for pieces of text. For example, \( x := w_0 \) is the text that describes an assignment of a value represented by a symbolic variable \( w_0 \) to the variable \( x \). On the other hand, \( x := w_0 \) is the predicative relation that defines the meaning of \( x := w_0 \). The distinction is important in the operational semantics, which manipulates pieces of text to define constraints.

The second component \( s \) is a UTP predicate, which defines a total assignment \( x := w \) of symbolic variables \( w \) to all variables \( x \) in scope, including the state components. State assignments, however, can also include declarations and undeclarations of variables using the constructs \texttt{var x := e} and \texttt{end x}. The state assignments define a value for all variables in scope. These values are represented by symbolic variables similarly to what is classically done in symbolic execution of programs [38].

Two examples of rules are given in Figure 2. The first rule defines the transitions arising from an input prefixing \( d?x : T \rightarrow A \); it is rule \( (\alpha.3) \) of Appendix A. The label of the transition is \( d?w_0 \), where \( w_0 \) is a symbolic variable. The constraint that \( w_0 \) is of the right type \( (w_0 \in T) \) is added to the constraint of the new configuration. The state of the new configuration is enriched, via the UTP sequence operator \( ; \), by a new component \( x \), which is assigned value \( w_0 \). The continuation of the new configuration is the action \( A \) in an environment enriched by \( x \) as defined by \texttt{let x • A}.

The second rule of Figure 2 defines the transitions arising from a guarded action \( g \& A \). The label of such a transition is empty, since the evaluation of \( g \) is not an observable event; \( g \) is added to the constraint of the new configuration taking into account the assignments in the current state \( s \). The continuation is \( A \).

Traces of a process are defined in the usual way, that is, as sequences of observable events. Due to the symbolic nature of configurations and labels, however, we can obtain from the operational semantics \textit{constrained symbolic traces}, or \textit{cstraces}, for short. These are pairs formed by a sequence of labels, that is, a symbolic trace, and a constraint over the symbolic variables used in the labels. Roughly speaking, the constrained symbolic trace can be obtained by evaluating the operational semantics, collecting the labels together, and accumulating the constraints over the symbolic variables.
variables used in the labels. Figure 3 gives some examples of cstraces of Chrono.

A trace is an instantiation of a cstrace, where the symbolic variables used in the labels are replaced by values satisfying the constraint. For instance, the two traces \(\langle \text{time}, \text{out}!0!0\rangle\) and \(\langle \text{tick}, \text{time}, \text{out}!0!1\rangle\) are instances of \(\text{cst2}\) and \(\text{cst3}\).

2.2. Testing in Circus

Gaudel’s long-standing testing theory [23] has been instantiated for Circus in [22]. The conformance relation considered in that work is process refinement: the UTP notion of refinement applied to state-rich processes.

As previously explained, the Circus testing theory takes the view that, in specifications, divergences are mistakes. In addition, since in a system under test (SUT), they are observed as deadlocks, altogether the results in [22] consider divergence-free specifications and SUT. For divergence-free models, the Circus refinement relation can be characterized by the conjunction of traces-refinement and the well known conf relation, as defined in [39], that requires reduction of deadlocks. This is proved in [40].

Accordingly, [22] defines separate exhaustive test sets for traces refinement and conf, namely \(\text{Exhaust}_T(SP)\) and \(\text{Exhaust}_{\text{conf}}(SP)\), which we briefly present here.

A test for traces refinement is constructed by considering a trace of the Circus specification and one of the events that cannot be used to extend that trace to obtain a new trace of the Circus specification [41]. Such events are called the forbidden continuations of the trace. For a specification SP, the exhaustive test set \(\text{Exhaust}_T(SP)\) includes all the tests formed by considering all the traces and all their forbidden continuations and inserting some special verdict events, as explained below.

For a finite trace \(s = \langle a_1, a_2, \ldots, a_n \rangle\) and an event (forbidden continuation) \(a\), we define the test process \(T_T(s, a)\) as follows:

\[
T_T(s, a) = \text{inc} \rightarrow a_1 \rightarrow \text{inc} \rightarrow a_2 \rightarrow \text{inc} \ldots a_n \rightarrow \text{pass} \rightarrow a \rightarrow \text{fail} \rightarrow \text{STOP}
\]

Extra special events inc, pass and fail are used to indicate a verdict. In the execution of a testing experiment, the test is run in parallel with the SUT and the last special event observed in a testing experiment provides the verdict. Due the possibility of nondeterminism, the submitted trace of the Circus specification is not necessarily performed by the SUT. The inc event indicates an inconclusive verdict: the SUT has not performed the proposed trace. If it does perform the trace, a pass event is observed, but if the SUT proceeds to engage in the forbidden continuation \(a\), then there is a fail event.
Example 1. For instance, a possible test of *Chrono*, based on the trace \langle tick, time \rangle and the forbidden continuation out.0.0 is:

\[
\text{inc} \rightarrow \text{tick} \rightarrow \text{inc} \rightarrow \text{time} \rightarrow \text{pass} \rightarrow \text{out.0.0} \rightarrow \text{fail} \rightarrow \text{Stop}
\]

This leads to the following definition of the exhaustive test set for traces refinement:

\[
\text{Exhaust}_T(SP) = \{ T_T(s, a) \mid s \in \text{traces}(SP) \land s \not\sim \langle a \rangle \notin \text{traces}(SP) \}
\]

The exhaustivity, that is, the equivalence of traces refinement to the absence of *fail* verdict when running all the tests of \(\text{Exhaust}_T(SP)\), is proved in [41] and [22] under – as usual in theoretical approaches to testing in the presence of nondeterminism – the complete testing assumption [42]: when a test experiment is performed a sufficient number of times all possible (nondeterministic) behaviours of the SUT are observed.

Traces and forbidden continuations are characterised symbolically leading to the definition of \(SE\text{Exhaust}_T(SP)\), an exhaustive set of symbolic tests based on cstraces and constrained symbolic forbidden continuations.

Example 2. An example of such a symbolic test for *Chrono*, based on the ctrace (\langle tick, time \rangle, true) and the forbidden constrained symbolic continuation defined as out.\(\alpha_0,\alpha_1\) : (\(\neg(\alpha_0 = 0 \land \alpha_1 = 1)\)) is as follows:

\[
\text{inc} \rightarrow \text{tick} : \text{true} \rightarrow \text{inc} \rightarrow \text{time} : \text{true} \rightarrow \text{pass} \rightarrow \text{out.}\alpha_0,\alpha_1 : (\neg(\alpha_0 = 0 \land \alpha_1 = 1)) \rightarrow \text{fail} \rightarrow \text{Stop}
\]

In [22] it is proved that \(\text{Exhaust}_T(SP)\) corresponds to all the tests that are valid instances (that is, that satisfy the constraints) of some symbolic test in \(SE\text{Exhaust}_T(SP)\).

The \text{conf} relation captures reduction of deadlock. Given \(SP_1\) and \(SP_2\), we have that \(SP_1 \text{ conf } SP_2\) if, and only if, whenever \(SP_2\) engages in a sequence of events, that is, a trace that can be accepted by \(SP_1\) as well, then \(SP_2\) can only deadlock if \(SP_1\) may as well. Formally, \text{conf} can be defined as follows:

\[
SP_2 \text{ conf } SP_1 \equiv \forall t : \text{traces}(SP_1) \cap \text{traces}(SP_2) \bullet \text{Ref}(SP_2, t) \subseteq \text{Ref}(SP_1, t) \quad \text{where } \text{Ref}(SP, t) \equiv \{ X \mid (t, X) \in \text{failures}(SP) \}
\]

For a trace \(t\) of a process \(P\) and a subset \(X = \{a_1, \ldots, a_n\}\) of the set of events of \(P\), noted \(aP\), the pair \((t, X)\) belongs to \(\text{failures}(P)\) if, and only if, after performing \(t\), \(P\) may refuse all events of \(X\). In other words, the parallel composition below may deadlock just after \(t\). We use \(\text{proc}(t)\) to represent a *Circus* process that accepts just the execution of \(t\) before finishing; it can be defined using prefixing, for example.

\[
P \parallel aP \parallel (\text{proc}(t); (a_1 \rightarrow P_1 \square \ldots \square a_n \rightarrow P_n))
\]

\(P \parallel aP \parallel Q\) is the parallel composition of the processes \(P\) and \(Q\) with synchronisation required on all the events of \(P\), that is, the events in the set \(aP\).
Thus, given a system under test SUT and a specification SP, for SUT \textit{conf} SP to hold, the definition requires that, after performing every one of their common traces, the failures of SUT are failures of SP. Consequently, after a trace \( t \) of SP, SUT may refuse all events refused by SP or accept some of them. Testing for \textit{conf} based on the refusals of SP would be, therefore, useless. What must be tested is that, after every trace \( t \) of SP, SUT cannot refuse all events in a set \( X \) of events such that \((t, X) \notin \text{failures}(SP)\). Such sets of events are called \textit{acceptance sets} of SP after \( t \).

Thus, tests for \textit{conf} are based on traces and acceptance sets. For a finite trace \( s = \langle a_1, a_2, \ldots, a_n \rangle \) and a(n acceptance) set \( X = \{x_1, \ldots, x_m\} \) of events, we define the \textit{Circus} test process \( T_F(s, X) \) as shown below.

\[
T_F(s, X) = \text{inc} \rightarrow a_1 \rightarrow \text{inc} \rightarrow a_2 \rightarrow \text{inc} \ldots a_n \rightarrow \text{fail} \\
\rightarrow (x_1 \rightarrow \text{pass} \rightarrow \text{Stop} \quad \ldots \quad \Box x_m \rightarrow \text{pass} \rightarrow \text{Stop})
\]

\textbf{Example 3.} An example of such a test for Chrono, based on trace \( \langle \text{tick} \rangle \) and on the acceptance set \( \{ \text{tick, time} \} \) is:

\[
T_F(\langle \text{tick} \rangle, \{ \text{tick, time} \}) = \text{inc} \rightarrow \text{tick} \rightarrow \text{fail} \\
\rightarrow (\text{tick} \rightarrow \text{pass} \rightarrow \text{Stop} \quad \Box \text{time} \rightarrow \text{pass} \rightarrow \text{Stop})
\]

An exhaustive test set of a specification SP for \textit{conf} is made of all tests formed by considering all traces of SP, and all the acceptance sets after each of them:

\[
\{ T_F(t, X) \mid t \in \text{traces}(SP) \land (t, X) \notin \text{failures}(SP) \}
\]

Actually \textit{Exhaust\textsubscript{conf}}(SP) is defined as a subset of the set above where only minimal acceptance sets are considered, since as soon as some event in a set \( X \) is accepted after a trace, any set containing \( X \) is an acceptance set after this trace. For instance, the test in Example 3 is not in \textit{Exhaust\textsubscript{conf}}(Chrono), but the two tests below are:

\[
T_F(\langle \text{tick} \rangle, \{ \text{tick} \}) = \text{inc} \rightarrow \text{tick} \rightarrow \text{fail} \rightarrow (\text{tick} \rightarrow \text{pass} \rightarrow \text{Stop}) \\
T_F(\langle \text{tick} \rangle, \{ \text{time} \}) = \text{inc} \rightarrow \text{tick} \rightarrow \text{fail} \rightarrow (\text{time} \rightarrow \text{pass} \rightarrow \text{Stop})
\]

The symbolic counterpart of \textit{Exhaust\textsubscript{conf}}(SP) is \( S\textit{Exhaust\textsubscript{conf}}(SP) \), defined in [22]. \( S\textit{Exhaust}_{T}(SP) \) and \( S\textit{Exhaust}_{conf}(SP) \) provide bases for defining strategies for test selection as definitions of subsets of \( \textit{Exhaust}_{T}(SP) \) and \( \textit{Exhaust}_{conf}(SP) \) via uniformity or regularity hypotheses [23] and adequate instantiations [22], or coverage criteria of the specification [28]. This paper addresses fault-based selection techniques.

The \textit{Circus} testing theory for traces refinement can be seen as a fault-based testing approach, because tests are constructed from (minimal) invalid traces. The fault considered in a particular test is very specific: a single forbidden continuation; the exhaustive test set considers all such possible faults. The theory for \textit{conf} testing considers other specific faults, namely refusals of the SUT that are not specified.

A practical question regards the use of more elaborated fault models. This is studied in the next section, and mutation operators are presented in Section 4.
3. Mutation testing in Circus

We assume that there is a specification (model), which is a Circus process that describes what the implementation should do. A mutant is also a Circus process, somehow related to the original specification; it represents a fault in that specification. In what follows, we may also refer to mutants as faulty models. In general, given a mutant defined as a Circus process, it can be used to generate tests to identify the fault it represents, that is, to “kill the mutant”. We apply the approach in [36] by Aichernig at al. for mutation testing based on refinement, but consider the particular case of state-rich process algebraic models, and Circus in particular.

A mutant FM is of interest if there exists at least one test that can kill it. This is not the case if it is a refinement of the specification. This is the counterpart at the model level of the well known problem of equivalent mutants at the program level. In such a case, the mutant is not a faulty model and so not relevant.

In Section 3.1 we formalise mutation testing when traces refinement is the conformance relation of interest. Section 3.2 presents an example: a mutant and the tests they generate. Section 3.3 considers mutation when testing against the conf conformance relation. Finally, in Section 3.4, we introduce a new kind of trace, closer to the text of the specification, to relate tests and mutation points in the specification.

3.1. Killing faulty models against traces refinement

In the context of traces refinement, we consider a faulty model FM to be of interest if it is not a traces refinement of the specification model SP. In this case, there is at least one trace of FM that is not a trace of SP; this is not the empty trace ⟨⟩, because ⟨⟩ is a trace of all processes. To detect the fault in FM, we can use a test $T_T(s, a)$ characterised by any of the minimal traces $s \sim ⟨a⟩$ of FM that are not traces of SP.

Formally, we define the set $FBTests_{SP}^{T}(FM)$ of fault-based tests characterised by FM with respect to a specification SP as shown below.

**Definition 1.**

$$FBTests_{SP}^{T}(FM) = \{s : \text{traces}(SP); \ a : \Sigma | s \sim ⟨a⟩ \in \text{traces}(FM) \setminus \text{traces}(SP) \bullet T_T(s, a)\}$$

This is the set of all tests $T_T(s, a)$, formed from traces $s$ of SP and events $a$ from $\Sigma$ such that $s \sim ⟨a⟩$ is a trace of FM, but not of SP. A mutant FM is killed by any test from $FBTests_{SP}^{T}(FM)$. As a direct consequence of its definition, we have that $FBTests_{SP}^{T}(FM)$ is a subset of $Exhaust_T(SP)$, since it contains tests $T_T(s, a)$, where $s \in \text{traces}(SP)$ and $s \sim ⟨a⟩ \notin \text{traces}(SP)$.

Before generating tests based on a mutant FM, a first step is the confirmation that it is not a traces refinement of the model SP. For that, it is of value to use a refinement model checker, like FDR [43] for CSP, for example, to check $SP \sqsubseteq_T FM$. If this does not hold, FDR provides a counterexample: a minimal trace of FM that is not a trace of SP. As said above, this identifies a test to detect the fault specified in FM.
process MutatedChrono ≡

...  

Run ≡ (tick → IncSec; (¬ (sec = 0) & IncMin)

□((sec ≠ 0) & Skip)))

□(time → out !(min, sec) → Skip)

• (AInit; (µ X • (Run; X)))

...

Figure 4: a mutated chronometer

3.2. A first mutant of Chrono and some tests that kill it

Figure 2 presents the mutant MutatedChrono of the Chrono process, which is obtained by the introduction of the negation (¬) operator in the first guard of the action Run. The following change in behavior arises from this mutation: like Chrono, MutatedChrono starts with the AInit operation that initialises min and sec to 0 and, after a tick, IncSec increases the value of sec to 1; afterwards, however, the mutant behaves nondeterministically, either like Chrono, that is, executing Skip and then Run again, or performing IncMin and then Run again, like Chrono in the case sec = 0. This erroneously leads to a state where min = 1 and sec = 1. This mutated state can be later observed via an output on the channel out following a time event.

Thus ⟨tick, time, out!(1, 1)⟩ is a trace of MutatedChrono, but not of Chrono, for which the only accepted event after ⟨tick, time⟩ is out!(0, 1). As seen above such traces define tests that kill the mutant. An example is the test below:

inc → tick → inc → time → pass → out!(1, 1) → fail → Stop

It is a member of FBTests^{Chrono}(MutatedChrono).

Actually, this test may kill the mutant since it is nondeterministic due to the overlap of the guards in the choice operator (for the distinction between “may kill” and “must kill”, see [44]). The test kills the mutant under the complete testing assumption.

3.3. Killing faulty models against the conf conformance relation

Given a mutant FM, it is of interest if ¬ (FM conf SP). In this case, there is at least one common trace s of SP and FM for which ¬ (Ref(FM, s) ⊆ Ref(SP, s)). Therefore, according to the definition of Ref(P, s), there is at least one set of events X such that (s, X) ∈ failures(FM), but (s, X) /∈ failures(SP).

The detection of the fault specified in FM with respect to conf is based on tests T_p(s, X) characterized by (s, X) ∈ failures(FM), where (s, X) /∈ failures(SP), and s is a trace s of SP and FM. The full set FBTests^{SP}(FM) of fault-based tests for conf characterized by FM with respect to SP is defined as follows.
Definition 2.

\[ FBTests^{SP}_{P}(FM) = \{ s : \text{traces}(SP) \cap \text{traces}(FM); X : \mathcal{P} \Sigma | (s,X) \in \text{failures}(FM) \setminus \text{failures}(SP) \bullet T_{P}(s,X) \} \]

As a direct consequence of the above definition, we have that \( FBTests^{SP}_{P}(FM) \) is a subset of \( Exhaust_{conf}(SP) \), since it contains tests \( T_{P}(s,X) \), where \( s \in \text{traces}(SP) \) and \( (s,X) \notin \text{failures}(SP) \). In words, \( X \) is an acceptance set of \( SP \) after \( s \).

**Theorem 1.** For every mutant \( FM \) of a specification \( SP \), the following statements are equivalent:

1. \( FM \) is of interest; and
2. \( FBTests_{P}^{SP}(FM) \neq \emptyset \lor FBTests_{P}^{SP}(FM) \neq \emptyset \).

**Proof.** If \( FM \) is of interest, it is not a refinement of \( SP \), that is, either it is not a traces refinement of \( SP \), or it does not satisfy \( FM \ conf \ SP \).

In the first case, as shown in [22], there exists some \( T \in Exhaust_{T}(SP) \) such that its execution against \( FM \) yields a fail verdict. By definition of \( Exhaust_{T}(SP) \), there are \( s \) and \( a \), such that \( T = T_{T}(s,a) \) and \( s \in \text{traces}(SP) \land s \sim (a) \notin \text{traces}(SP) \). From the definition of \( T_{T}(s,a) \), since the fail event is reached, \( s \sim (a) \) is a trace of \( FM \). Thus, from Definition 1, \( T \) belongs to \( FBTests_{T}^{SP}(FM) \), and so \( FBTests_{P}^{SP}(FM) \neq \emptyset \).

With a similar argument, the second case implies \( FBTests_{P}^{SP}(FM) \neq \emptyset \).

Conversely, if \( FBTests_{P}^{SP}(FM) \neq \emptyset \), there exists some \( T = T_{T}(s,a) \), where \( s \in \text{traces}(SP) \) and \( s \sim (a) \in \text{traces}(FM) \setminus \text{traces}(SP) \). \( T \) belongs to \( Exhaust_{T}(SP) \) and by construction yields a fail verdict when executed against \( FM \). Therefore, from the exhaustivity result of [22], \( FM \) is not a traces refinement of \( SP \).

The proof that \( FBTests_{P}^{SP}(FM) \neq \emptyset \) implies that \( \sim \) \( FM \ conf \ SP \) is similar.

In Theorem 1, we formalise the previously introduced notion of mutants of interest: a mutant is of interest if its fault can be exposed by, at least, a test.

**Example 4.** Coming back to MutatedChrono, another change of behavior is that it introduces a deadlock. When the mutated external choice is reached in a state where \( sec = 0 \), because all the possible choices are guarded by the negation of this condition, there is a deadlock. Due to the equation \( sec' = (sec + 1) \mod 60 \) in the IncSec schema, it occurs after sixty tick events. After such a trace, Chrono must accept one more tick event, or one time event, but the mutated specification refuses both. This leads to the following tests, each of them killing the mutant under the complete testing assumption.

\[(inc \rightarrow tick)^{60} \rightarrow fail \rightarrow tick \rightarrow pass \rightarrow Stop\]
\[(inc \rightarrow tick)^{60} \rightarrow fail \rightarrow time \rightarrow pass \rightarrow Stop\]

We use \((inc \rightarrow tick)^{60}\) to denote a prefixing action where the events \( inc \) and \( tick \) are offered in alternation, starting with \( inc \), 60 times. □
When generating tests based on given a mutant $FM$, a first step is the confirmation that it is a traces refinement, but not a failures refinement of $SP$. If we can use a refinement model checker, we can check $SP \sqsubseteq_T FM$, and then use the counterexample for $SP \sqsubseteq_F FM$. In the case of FDR, for example, the counterexample is a minimal set of acceptances of $FM$ that is not a set of acceptances of $SP$. Alternatively, it gives a set of refusals of $FM$ that is not a set of refusals of $SP$. It is this set of refusals that can be directly used to define a test to detect the fault specified in $FM$.

In our framework, a set of mutants $M$ of $SP$ defines a set

$$T^M_T \equiv \{ M \bullet FBTests^{SP}_T(m) \}$$

of subsets of $Exhaust_T(SP)$ and a set

$$T^M_F \equiv \{ M \bullet FBTests^{SP}_F(FM) \}$$

of subsets of $Exhaust_{conf}(SP)$. Therefore, $M$ is the basis of a test selection method in the sense of [22]. Besides, given a test suite $T$, it is adequate for $M$ if, for each $m \in M$, $T \cap FBTests^{SP}_T(m) \neq \emptyset$ or $T \cap FBTests^{SP}_F(FM) \neq \emptyset$. From Lemma[3], we know that for a set $M$ of mutants of interest, there is always an adequate test suite.

3.4. Specification traces and mutation points

Mutations are related to the text of a specification. Traces and even constrained symbolic traces, however, are not related to the text of the specification. They record a possible history of interactions, and it may well be the case that, in some specific situations, we can relate interactions to events and communications in the text of specification. On the other hand, but there is no record of guards and data operations that may have been evaluated or executed in the path to that interaction.

As an example, we consider the constrained symbolic trace $cst3$ in Figure 3. Since there is only one communication via $out$ in the text of Chrono, in this special case, we can relate $out!\alpha_0!\alpha_1$ to the anti-penultimate line of its definition. On the other hand, $cst3$ has no record of $AINit$ and $IncSec$, and of the guards $sec = 0$ and $sec \neq 0$, which are considered in the path to that interaction and may be the object of a mutation.

Therefore, we use specification traces, as defined in [45, 28], to build the tests aimed at killing a mutant. In [28], specification traces are used to consider data-flow coverage, which is also based on the text of a specification. While cstraces are useful for trace selection based on constraints on the traces, they do not support selection based on the text of the specification, as we explain in the sequel.

In specification traces, labels are pieces of the specification: guards (predicates), communications, data operations (schemas) or simple Circus actions. In case there are repetitions of identical text pieces in the Circus specification, different occurrences are distinguished in the labels using textual tags. The syntactic category of Labels is defined in Figure 5, the sets $Pred$, $Exp$, $CName$, $VName$, and $Schema$ are those of the Circus predicates, expressions, channel and variable names, and Z schemas [46].

In Figure 6, we present two rules of the transition system that characterises specification traces. These transition rules correspond to those for the operational semantics shown in Figure 2. We note that, the same notion of configuration is used and the transitions are the same, except for the labels. For instance, for an input, the label $d?u_0$
Label ::= Pred | Comm | LAct
Comm ::= ε | CName | CName!Exp | CName?VName
     | CName?VName : Pred
LAct ::= VName* : [Pred, Pred] | Schema | VName := Exp
       | var VName : Exp | var VName := Exp | end VName

Figure 5: Syntax of specification labels.

\[
\begin{align*}
\frac{c \land T \neq \emptyset \quad x \notin \alpha}{x \notin \alpha} \\
(c \mid s \models d?x : T \rightarrow A) \Rightarrow (c \land w_0 \in T \mid s ; \text{var}x := w_0 \models \text{let } x \bullet A)
\end{align*}
\]  

(1)

\[
\frac{c \land (s; g)}{c \land (s; g)}
\]

(2)

In the operational semantics uses a symbolic variable \( w_0 \), while in the specification traces it refers to the variable \( x \) used in the specification. Moreover, the transition for a guarded action \( g \& A \) is no longer unlabelled, but records the guard \( g \).

In Figures 7 and 8, we list some specification traces for the processes \( \text{Chrono} \) and \( \text{MutatedChrono} \). The use of text pieces from the specifications in labels allows the identification and selection of traces that reach textual constructs affected by mutation.

Remark. In [28], a subset of specification traces, \( \text{sptraces} \), is considered for the definition of tests satisfying data-flow coverage criteria, namely, the set of specification traces where the last event is an observable event. Some of the specification traces given in Figures 7 and 8 are not sptraces. It is the case of \( \text{spect1} \) and \( \text{spect}^{'1} \), and of all the traces in \( \text{Setspect}^{'5} \). The specification traces in this last set, for example, are of great interest since they lead to a deadlock that is not in the original specification, and thus provide bases for obtaining tests of \( FBTests^p_{\text{Chrono}}(\text{MutatedChrono}) \). □

Converting a specification trace to a cstrace requires the definition of an operational semantics for labels. Figure 9 presents its transition rules for input and guard labels. We refer to Figure 2 for the corresponding rules of the operational semantics. Like in the operational semantics, the configuration is a triple, but here, instead of a process or action, there is a label associated with a constraint and a state assignment. Labels with no guard, but with an input or output communication, are handled in the same way as input and output prefixes in the operational semantics. When there is a label \((g, e, A)\), with a guard that may be different from \( \text{True} \), if the guard holds in the current state then there is a transition to a label \((e, A)\) with guard \( \text{True} \), or no guard, for short. The
transition is unlabelled, like in the operational semantics.

The similarity between the operational semantics of labels and of Circus is not surprising. Conversion of specification traces (of labels) to a cstrace recovers the operational semantics of the Circus texts captured in the specification traces.

In Figures 7 and 8 we give the constrained symbolic traces converted from those specification traces listed in Figures 7 and 8. The trace \(cst'4\) is that used in Section 3.2 as a basis for the first test that kills MutatedChrono. The trace \(cst'5\) is the unique translation of all the traces in \(Setspect'5\); it is the basis of the two other killer tests given in Section 3.2. The conversion procedure of sptraces into cstraces is given in [28] and trivially generalises to specification traces. As seen above, several specification traces may correspond to the same cstrace. This follows from the fact that cstraces record only observable symbolic events, while specification traces record internal events and may distinguish different ways of enchaining the same observable events.

To summarise, in considering mutation testing in Circus we use three kinds of traces: specification traces, cstraces, and standard traces. We perform the selection among specification traces and then generate from those some killer tests belonging to \(FBTests^SP(FM)\) and \(FBTests^{sp}(FM)\), which are defined as sets of concrete tests based on standard traces. Since the operational semantics defines the traces of a speci-
\[
\frac{c \land (s; g)}{(c \mid s \models (g, e, A)) \xrightarrow{d} (c \land (s; g) \mid s \models (e, A))}
\]
\[
(c \mid s \models (g, e, A)) \xrightarrow{d} (c \land (s; g) \mid s \models (e, A))
\]
\[
(c \mid s \models (d?x : T, A)) \xrightarrow{d} (c \land w_0 \in T) \mid s; \text{var } x := w_0 \models \text{let } x \cdot A)
\]

Figure 9: Operational semantics of labels

\[
cst'1 : ((\text{tick}), \text{true})
cst'2 : ((\text{time}, \text{out}!\alpha_0!\alpha_1), \alpha_0 = 0 \land \alpha_1 = 0)
cst'3 : ((\text{tick}, \text{time}, \text{out}!\alpha_0!\alpha_1), \alpha_0 = 0 \land \alpha_1 = 1)
cst'4 : ((\text{tick}, \text{time}, \text{out}!\alpha_0!\alpha_1), \alpha_0 = 1 \land \alpha_1 = 1)
cst'5 : ((\text{tick})^{60}, \text{true}) \quad \text{[deadlock]}
\]

Figure 10: Constrained symbolic traces for MutatedChrono

fication as cstraces, there is an intermediate form of the tests based on cstraces, that is, symbolic killer tests, that need to be adequately instantiated into some concrete tests.

We must take into account that a specification trace corresponds to one cstrace, but that several specification traces may correspond to the same cstrace, as seen above, and that a specification trace of \( FM \) that is not a specification trace of \( SP \) may lead to a cstrace that is the translation of another specification trace of \( SP \). Given a mutant \( FM \) of \( SP \), we define a notion of relevant specification trace of \( FM \).

**Definition 3.** Given a specification \( SP \) and a faulty model \( FM \) obtained by mutation of \( SP \), a specification trace of \( FM \) is relevant if:

- it is not a specification trace of \( SP \) and its conversion into a cstrace is not a cstrace of \( SP \), or
- one of the instantiations of its conversion into a cstrace is part of some failure of \( FM \) that is not a failure of \( SP \).

The first case is the starting point for obtaining some tests in \( FBTests_{SP}^{SP}(FM) \) and the second case for some tests in \( FBTests_{SP}^{SP}(FM) \).

To determine whether a specification trace of \( FM \) is relevant, we need to compare its cstrace to those of \( SP \). We note that in the Circus testing theory, we use unique (up to predicate equivalence) symbolic representatives of these traces using a fixed ordered alphabet of symbolic variables. That allows a uniform account of these traces, and simplifies the management of names by avoiding renaming complications.

If there are no relevant specification traces of \( FM \), it means that there exist no test for killing \( FM \), that is, the effect of the mutation is not observable, neither for traces, nor for failures. \( FM \) is a refinement of \( SP \) and is not a mutant of interest.
The existence of non-relevant mutated specification traces is due to the possibility of specifying systems in an abstract way, with hidden operations on some state: the consequences of a mutation of such operations may not be observable. This phenomenon is not specific to Circus and similar issues are likely to occur in model-based mutation testing as soon as there is a significant abstraction gap between the model and the SUT.

It is very likely that some mutations affecting the hidden state can be identified as prone to producing non-relevant specification traces, and then avoided in a particular test-selection heuristic. These points are the subject of future work.

In conclusion, given a mutation of a Circus specification, the principle of the test-generation process that we propose is as follows:

1. Select a specification trace $\text{spec}$ of $FM$ that reaches the mutation point;
2. Convert it into its corresponding cstrace $cst$;
3. Check whether $cst$ is a cstrace of $SP$;
4. If not, instantiate $cst$ into a concrete trace and build the corresponding tests of $FBTests_{SP}^{ST}(FM)$ as defined in Section 3.1;
5. Check whether some instantiations of $cst$ leads to failures that are not failures of $SP$ and build the corresponding tests of $FBTests_{SP}^{ST}(FM)$, as defined in Section 3.3.

We discuss in Section 5 some tools to support this process. First, in the next section, we present operators to produce mutants.

4. Mutation operators

A mutation operator $Op$ is a function that generates a set of mutants for a given specification $SP$. In each mutant in $Op(SP)$, one fault is inserted. Such an operator only yields well-typed, syntactically correct, mutants. A mutation operator is valid for a specification, if it generates at least one mutant of interest.

In this section, we present a list of mutation operators for Circus. Many of the mutation operators of CSP presented in [31] by Srivatanakul et al. are directly applicable to Circus. These are discussed in Section 4.1. For the data and state aspects of Circus, we can benefit from some mutation operators based on fault classes for predicates, like those presented by Kuhn in [32] and enriched by Black et al. in [33]. These are discussed in Section 4.2. We need to take into consideration, however, the specific features and particularities of our target language, Circus.

4.1. Modification of behavioural operators

Three classes of mutation operators are suggested for CSP in [31]: process definition, expression, and parameter modification operators. Each operator from the first two classes is considered in this section, and we introduce some variations better suited to Circus models. When adequate, we refer to the rules of the Circus operational semantics that formalise the affected behaviors.

Parameters are not as important in Circus as they are in CSP. Since Circus processes can have a state, parametrisation is typically used to define generic processes. In this
<table>
<thead>
<tr>
<th>Class</th>
<th>Abbreviation</th>
<th>Operator</th>
<th>Source</th>
<th>OPS Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>ped</td>
<td>Event Drop</td>
<td>CSP</td>
<td>9, 30</td>
</tr>
<tr>
<td></td>
<td>per</td>
<td>Event Replacement</td>
<td>CSP</td>
<td>9, 30</td>
</tr>
<tr>
<td></td>
<td>pes</td>
<td>Event Swap</td>
<td>CSP</td>
<td>9, 30</td>
</tr>
<tr>
<td></td>
<td>pei</td>
<td>Event Insert</td>
<td>CSP</td>
<td>9, 30</td>
</tr>
<tr>
<td></td>
<td>pco</td>
<td>Choice Operator</td>
<td>CSP</td>
<td>18 - 24</td>
</tr>
<tr>
<td></td>
<td>ppoParSeq</td>
<td>Parallel Composition</td>
<td>CSP</td>
<td>14,15,25-30</td>
</tr>
<tr>
<td></td>
<td>ppoSeqPar</td>
<td>Sequential Composition</td>
<td>CSP</td>
<td>25 - 30</td>
</tr>
<tr>
<td></td>
<td>ppoSeqInt</td>
<td>Interleave</td>
<td>CSP</td>
<td>25 - 30</td>
</tr>
<tr>
<td></td>
<td>ppoParInt</td>
<td>Interleave</td>
<td>CSP</td>
<td>25 - 30</td>
</tr>
<tr>
<td></td>
<td>ppoNameSet</td>
<td>Parallel State Writing</td>
<td>Circus</td>
<td>25 - 30</td>
</tr>
<tr>
<td>Communic.</td>
<td>pmr</td>
<td>Message Replacement</td>
<td>CSP</td>
<td>10 - 12</td>
</tr>
<tr>
<td></td>
<td>pcr</td>
<td>Channel Replacement</td>
<td>CSP</td>
<td>10 - 12</td>
</tr>
<tr>
<td></td>
<td>pci</td>
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<td>CSP</td>
<td>10 - 12</td>
</tr>
<tr>
<td></td>
<td>pce</td>
<td>Communication Elimination</td>
<td>CSP</td>
<td>10 - 12</td>
</tr>
<tr>
<td></td>
<td>pcs</td>
<td>Communication Swap</td>
<td>CSP</td>
<td>10 - 12</td>
</tr>
<tr>
<td>Name/Hide</td>
<td>pprAction</td>
<td>Action Name</td>
<td>Circus</td>
<td>31 - 33</td>
</tr>
<tr>
<td></td>
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<td>Schema Name</td>
<td>Circus</td>
<td>31 - 33</td>
</tr>
<tr>
<td></td>
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<td>Hide Events</td>
<td>Circus</td>
<td>31 - 33</td>
</tr>
<tr>
<td></td>
<td>pprUnhide</td>
<td>Unhide Events</td>
<td>Circus</td>
<td>31 - 33</td>
</tr>
<tr>
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<td>eni</td>
<td>Negation Insert</td>
<td>CSP</td>
<td>17</td>
</tr>
<tr>
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<td>eniGuard</td>
<td>Guard Negation</td>
<td>CSP</td>
<td>17</td>
</tr>
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<td>CSP</td>
<td>17</td>
</tr>
<tr>
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<td>CSP</td>
<td>17</td>
</tr>
<tr>
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<td>CSP</td>
<td></td>
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<td>CSP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>eak</td>
<td>Add k to Operand</td>
<td>CSP</td>
<td></td>
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<tr>
<td></td>
<td>esk</td>
<td>Sub k from Operand</td>
<td>CSP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ead</td>
<td>Operand Replacement</td>
<td>CSP</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Mutation operators for Circus

In this case, parameters play the role of global constants in the scope of the process definition. We, therefore, do not consider parameter operators here.

Following the terminology in [31], synchronization events, that is, communications without value passing, are called simply "events". When values are passed, we refer to the events as "communications". Table 1 lists the operators presented in this section, identifying their classification, abbreviation, name, source and, when available in Appendix A, the associated operational semantics rules. The source column displays CSP for operators originally proposed for CSP, CSP* for operators adapted from CSP to match Circus constructs, and Circus for operators designed specifically for Circus.

We describe the operators as functions from texts (of actions) to texts, and identify conditions in which they can or cannot be applied. A mutated process is obtained by applying one of these functions to one of its actions.
**process** `ChronoEDropTime` ≡

... 

`Run` ≡ `(tick → IncSec; ((sec = 0) & IncMin)

\((sec ≠ 0) & Skip)))

\((out ! (min, sec) → Skip)

• (AInit; (μ X • (Run; X)))

... 

Figure 11: Mutation of `Chrono` after dropping `time`

In the sequel, we present mutations of events and communications, choice and concurrency operators, name references, and hiding.

4.1.1. **Mutations of events**

**Event Drop.** `(ped)` removes one (arbitrary) occurrence of a prefixing event. Such mutation is likely to produce processes that are not a refinement of the original specification in two ways: the removal of observable events from some traces and the possibility of deadlock introduction in parallel compositions. This can be checked in the rules (A.2) and (A.6) of the `Circus` operational semantics, reproduced in Appendix A, where output and parallelism are described. The definition of the `ped` operator is as follows.

```
ped(A[e→]) = A[ ]
```

**Remark.** We use `A[t₁]` to indicate that in the text of action `A` there is an occurrence of term `t₁`. There may be several such occurrences and we assume that we can distinguish them (via their position in the text, for example). `A[t₁]` refers to a particular occurrence. A subsequent reference to `A[t₂]` denotes the action obtained by replacing the occurrence of `t₁` originally singled out by `t₂`. In particular, `A[ ]` as used above denotes the text of `A` with this occurrence replaced by an empty term. □

In using the above operator and others to follow, the terms singled out in the action parameter, like `e →` in `A[e→]` above, for example, need to be chosen.

**Example 5.** Figures [11] and [12] show the mutants of the `Chrono` process obtained via the mutations: `ped(Chrono[t ime→])` and `ped(Chrono[tick→])`, which remove the occurrences of the synchronization events `time` and `tick` from the `Run` action. Among the traces of `ChronoEDropTime` that are not traces of `Chrono`, there are `(out !(0, 0))` and `(tick, out !(0, 1))`, which lead to the tests below:

```
pass → out !(0, 0) → fail → Stop
inc → tick → pass → out !(0, 1) → fail → Stop
```

They are members of `FBTests_{Chrono}(ChronoEDropTime)`.  

18
process ChronoEDropTick ⊆

\[
\begin{align*}
Run & \equiv (IncSec; ((sec = 0) & IncMin) \\
& \quad \Box((sec \neq 0) & Skip))) \\
& \quad \Box(time \to out !(min, sec) \to Skip) \\
& \bullet (AInit; (\mu X \bullet (Run; X)))
\end{align*}
\]

... Figure 12: Mutation of Chrono after dropping tick

ChronoEDropTick is an example of a divergent mutant, since Run may recurse indefinitely in an endless series of internal actions IncSec and IncMin. without ever communicating with the environment. Thus, it is discarded.

□

Event Replacement. (per) replaces an event by another one within the current local scope (action) or the global scope (process). It affects traces in similar ways as the ped operator, as described by the same rules of the operational semantics.

\[\text{per}(A[e\to], f) = A[f\to]\]

Event Swap. (pes) swaps two consecutive synchronization events in an action definition. If we apply it only to distinct events, this operator is prone to yielding mutants of interest, although this cannot be assured. For example, swapping a and b in \[a \to b \to \text{STOP} \square b \to a \to \text{STOP}\] leads to a traces refinement. The behavior is defined by the same rules (A.2) and (A.6) of the Circus operational semantics.

\[\text{pes}(A[e\to f\to]) = A[f\to e\to] \text{ where } e \neq f\]

Event Insert. (pei) inserts an event by duplication. The mutated action may not be of interest if the duplication occurs inside a loop.

\[\text{pei}(A[e\to]) = A[e \to e\to]\]

This concludes our list of event mutation operators.

4.1.2. Mutations of choice and concurrency operators

The following operators target choice and concurrency operators.

Choice Operator. (pco) replaces the external choice by the internal choice operator. From rules (A.4) and (A.8) to (A.11) of the operational semantics, we observe that such mutation may introduce deadlocks. The traces of the original and mutated actions are the same, so we always have a traces refinement. Therefore, the only error that may be introduced by such a mutation is a forbidden deadlock.

\[\text{pco}(A[\Box]) = A[\square]\]

We note that replacing an internal with an external choice is not of interest, since \(A \Box B\)
is refined by $A \boxplus B$, whether we consider traces or failures refinement.

**Parallelism and sequence.** (ppo) In [31], this operator can be used to replace an interleaving, a parallel or a sequential composition with each other. For Circus, we need to consider manipulation of state values in concurrent actions. We, therefore, distinguish the possible mutations for each type of composition.

Parallel composition of actions requires the explicit specification of which variables are available for writing by each concurrent action. For instance, in the Circus parallel composition $A \llbracket \text{NS}_a \mid \text{CS} \mid \text{NS}_b \rrbracket B$ values written by $A$ into the state variables are only kept for the variables with names in the name set $\text{NS}_a$. The same holds for the action $B$ and the name set $\text{NS}_b$. These sets must be disjoint. Any change of value not matching a name in the respective specified set is cancelled after the parallel composition ends (see rules (A.5) to (A.7) of the operational semantics). There are several interesting possibilities for injecting faults in parallel composition operators. For instance, to empty one or both name sets in a parallel composition is likely to yield unexpected state configurations and is defined by the following operation.

$$\text{ppoNameSet}(A[\text{NS}]) = A[\{\}].$$

$\text{NS}$ refers to a name set in a parallel composition. Removing or inserting arbitrary elements in $\text{NS}$ and other variations of this operator might also be of interest, provided the disjointness of the sets on both sides of the composition is preserved.

We define some specific operators for mutating the nature of the compositions. Such mutations are likely to cause substantial observable changes, although there is no guarantee that the result is a mutant of interest. Specific operators for changing parallel to sequential and the inverse are defined as follows.

$$\text{ppoParSeq}(A[B \llbracket \text{NS}_b \mid \text{CS} \mid \text{NS}_c \rrbracket C]) = A[B; C]$$

$$\text{ppoSeqPar}(A[;]$, $\text{CS}) = A[\llbracket \text{CS} \rrbracket]$$

The new sequential composition introduced by $\text{ppoParSeq}$ ignores the extra parameters of the original parallel composition, that is, $\text{NS}_a$, $\text{CS}$, and $\text{NS}_b$, and the new parallel composition introduced by $\text{ppoSeqPar}$ is designed to synchronize on all channels in a given set $\text{CS}$ and has no write access to any state values. We also define operators for mutating any composition into an interleaving.

$$\text{ppoParInt}(A[\llbracket \text{CS} \rrbracket]) = A[\{\}].$$

$$\text{ppoSeqInt}(A[;]) = A[\{\}].$$

Other forms of parallelism may be considered as well, but we do not pursue these here. The needed considerations in all cases are similar to those above.

**4.1.3. Mutations of communications**

The following mutation operators target communications, whose behaviours are described in rules (A.2) and (A.3). For the sake of conciseness, we do not discuss communications with multiple inputs or outputs.

The removal of an input communication can potentially introduce a syntax error, because it implicitly declares a new variable. Except when the input variable is never
used, we may end up with references to variables that are not declared. For mutation
operators that change or remove input communications, we, therefore, introduce a dec-
laration of the replaced or removed variable. A Circus variable declaration introduces
the variable in scope initialised with an arbitrary value from the variable domain.

Message Replacement. \((\text{pmr})\) changes the name of a variable used in a communication
to another name of a variable of the same type, selected from the current scope. As
explained above, missing variable names due to the introduced mutation are redeclared.

\[
\text{pmr}(A[c!e[x]->], y) = A[c!e[y]->] \\
\text{pmr}(A[c?x->], y) = A[\text{var } x : T \cdot c?y->]
\]

\(T\) is the type of channel \(c\) (and, therefore, of the input variable \(x\)).

Channel Replacement. \((\text{pcr})\) changes the name of a communication channel to another
channel name of the same type.

\[
\text{pcr}(A[c!e->], d) = A[d!e->] \\
\text{pcr}(A[c?x->], d) = A[d?x->]
\]

Communication Insert. \((\text{pci})\) is similar to the event insert \((\text{pei})\) operator, but applied to
a communication instead of a synchronization event. It inserts a new communication
by duplicating an existing one.

\[
\text{pci}(A[c!e->]) = A[c!e -> c!e->] \\
\]

Communication Elimination. \((\text{pce})\) removes one arbitrary input or output communi-
cation from an action definition. As for the message replacement \((\text{pmr})\) operator, if
the eliminated communication is an input, a variable declaration must be introduced to
declare the input variable and avoid syntactic errors.

\[
\text{pce}(A[c?x->]) = A[\text{var } x : T \cdot ] \\
\text{pce}(A[c!e->]) = A[ ]
\]

If the mutated action terminates or deadlocks, it has maximal traces. If the eliminated
communication contributes only to the last events of maximal traces, its elimination
leads to an action that is a traces refinement of the original action.

Communication Swap. \((\text{pcs})\) swaps two consecutive communication events, similarly
to the event swap \((\text{pes})\) operator.

\[
\text{pcs}(A[c1!e1 -> c2!e2->]) = A[c2!e2 -> c1!e1->] \\
\text{pcs}(A[c1!e -> c2?x->]) = A[c2?x -> c1!e->], \text{ provided } x \text{ is not free in } e \\
\text{pcs}(A[c1?x -> c2!e->]) = A[\text{var } x : T \cdot c2!e -> c1?x->]
\]

When swapping \(c1\) and \(c2\) where \(c1\) is used in an input that declares a variable that
may be used in an expression communicated by \(c2\), this change leads to a syntactic
error. To avoid that, a declaration of the input variable is introduced.
4.1.4. Mutations of name references and hiding

Name Replacement. (ppr) substitutes name references in the right hand side of an action definition by other process names in scope, including STOP and SKIP. For Circus, we expand this operator to include the manipulation of schema names.

\[
\text{pprAction}(A[A_1], A_2) = A[A_2] \\
\text{pprSchema}(A[S_1], S_2) = A[S_2]
\]

We also introduce two new operators for hiding and unhiding events and communications. The impact of such mutations on observable behavior is similar to event and communication insertion or removal. The channel set for the hiding is an arbitrary subset of the channels in scope. The operational semantics rules describing the behavior of the hiding operator are (A.12) and (A.13).

\[
\text{pprHide}(A_1[A_2], CS) = A_1[A_2 \setminus CS] \\
\text{pprUnhide}(A_1[A_2 \setminus CS]) = A_1[A_2]
\]

Similar operators for hiding are also useful at the action level.

4.2. Expression modification operators

In Circus specifications, some logical and data aspects are modelled along with the definitions of interactions via events. For instance, models typically include guard predicates, variable definitions and assignments, and also data operations defined using $Z$ schemas. We consider all these forms of data modelling in the design of mutation operators that capture data and logic faults.

Some fault classes for predicates occurring in software specifications have been proposed by Kuhn in [32]. They seem pertinent if we consider plausible modelling mistakes in Circus: variable reference, variable negation, expression negation, associative shifting, operator reference, and missing expressions. We also consider the expression operators introduced for CSP in [31], since they cover most of the mentioned fault classes. Finally, to complement the fault-classes coverage, we also introduce some syntactical operators for Circus expressions inspired by the work of Black et al. [33].

Negation Insertion. (eni) inserts the logical negation operator ($\neg$) before a boolean variable. This mutation is specially interesting when it affects guards, so we have a more specific version of this operator targeting the negation of guards only.

\[
eni(A[e]) = A[\neg e] \\
eniGuard(A[g \&]) = A[\neg g \&]
\]

where $e$ is a boolean expression in any Circus context, an action or a schema. For example, mutatedChrono is obtained from Chrono via $eniGuard(Chrono[(sec = 0)\&])$.

Logical Operator. (elr) exchanges between the logical “and” ($\land$) and “or” ($\lor$) operators. Other logical connectors might be considered, although the most used and more subject to modelling mistakes are these mentioned [31].

\[
elr(A[\land]) = A[\lor] \\
elr(A[\lor]) = A[\land]
\]
Logical Operand. `(eld)` introduces mutations by replacing variable and expression logical operands with `true` or `false` constant values.

\[
\text{eld}(A[b], \text{true}) = A[\text{true}]
\]
\[
\text{eld}(A[b], \text{false}) = A[\text{false}]
\]

Arithmetic Operator. `(ear)` replaces a basic arithmetic operator with one of the three others. The four operators considered are sum, subtraction, multiplication and division.

\[
\text{ear}(A[\text{op}_1], \text{op}_2) = \text{op}_1, \quad \text{where } \text{op}_2 \in \{+, -, *, /\} \land \text{op}_1 \neq \text{op}_2 \implies \text{P}[\text{op}_2]
\]

Unary Insertion. `(eur)` inserts the minus modifier in front of an arithmetic expression. The variable \(e\) stands for an arithmetic expression in a process \(P\).

\[
\text{eur}(A[e]) = A[-e]
\]

Add to Operand. `(eak)` increments an arithmetic operand by an integer constant \(k\). The variable \(v\) stands for a numeric variable used in an expression in any schema or action.

\[
\text{eak}(A[v], k) = A[(v + k)]
\]

Subtract from Operand. `(esk)` is similar, but subtracts the integer constant \(k\).

\[
\text{esk}(A[v], k) = A[(v - k)]
\]

Arithmetic Operand. `(ead)` arbitrarily replaces a numeric variable used as an arithmetic operand with another, keeping the types compatible. The variables \(v\) and \(u\) stand for numeric variables of the same type.

\[
\text{ead}(A[v], u) = A[u]
\]

Relational Operator. `(err)` replaces any of the relational operators \(<, \leq, >, \geq, =, \neq\) with any of the others from this same set.

\[
\text{err}(A[\text{op}_1], \text{op}_2) = \text{op}_1, \quad \text{where } \text{op}_2 \in \{<, \leq, >, \geq, =, \neq\} \land \text{op}_1 \neq \text{op}_2 \implies A[\text{op}_2]
\]

A mutation operator is `ideal` for a specification if it generates only mutants of interest; an ideal operator never leads to a refinement. Ideality is a strong requirement, not always achievable. None of the operators above is ideal. In fact, there can be no ideal operator for Circus: a single change to a process definition can never be guaranteed to lead to a non-refinement for every process. This can be seen by considering a process \(Q\), an arbitrary mutation operator \(Op\), and a process \(P\) defined as \(P = Q \cap Op(Q)\). In applying \(Op\) to \(P\), it is always possible to obtain \(P' = Op(Q) \cap Op(Q)\). Properties of Circus guarantee that \(P' = Op(Q)\), which does refine \(P\).

4.3. Comparison with mutation testing based on LOTOS

Several specification languages make it possible to mix data type and behaviour descriptions. The approach followed above for the definition of a set of mutation operators can be easily transposed to them. We take as an example the full LOTOS
specification language, whose mutations have been studied in [47], and whose testing
theory is developed in [25]. In a few words, LOTOS combines algebraic data type
specifications and parameterised process definitions.

The LOTOS notation for process definition is syntactically close to those of Circus
and CSP; however, there are semantic differences that arise, as far as testing is con-
cerned, in the definition of refusals and acceptance sets. Given the definition of these
sets, symbolic exhaustive test sets have been defined for conf [24] and for the ioco [11]
conformance relation [25]. The main difference to Circus is the notion of state, which
does not exist in LOTOS, and is simulated by process parameters like in CSP.

In [47], the authors propose a set of mutation operators. Most of them are not
special to LOTOS and, as ours, have been taken or slightly adapted from [33] and [31].
They correspond to those indicated with source CSP or CSP∗ in Table 1 and seem to
provide a kernel of mutation operators for specification languages of this category. The
few specific operators defined in [47] and here are related to parameters in LOTOS,
and to action and schema names in the case of Circus.

5. Tool support

To support Circus mutation testing and explore the practical aspects of our tech-
nique, we have implemented a prototype tool in Java to mutate specifications using
the mutation operators of Section 4. Syntax-tree manipulation is provided by the CZT
framework [48], using the Circus parser extension [49].

At the current stage, the prototype provides a simple command line interface that
takes as inputs a mutation operator reference and a LaTeX Circus specification, ac-
cording to the CZT style guide for Circus[1]. The output is presented as LaTeX Circus
specifications, one for each mutation produced by the selected operator. In Table 2 we
show the number of mutants produced by each operator when applied to Chrono (in
Figure 1). Operators not applicable to this example have not been considered.

Once the mutants are generated, we have to generate tests to kill them. We present
below two approaches for the generation of mutant-killing test cases.

The first approach requires the use of a model checker. Similar approaches for
generating test cases using model checkers are popular; see, for instance, [50] for a
survey. In our case, the checker is used to establish whether a generated mutant is a
refinement of the original specification and, if not, to yield some counterexamples that
provide a basis for building killer tests as illustrated in Section 3.

For Circus, there is no mature refinement model checker available at this time. It
is not the objective of our work to develop one (and there are ongoing efforts [51, 52]
in this direction). However, for some Circus specifications, we can overcome this
barrier via a translation of Circus models to CSP and the use of a well-known, mature
refinement checker for CSP, FDR [53]. We detail this approach in Section 5.1.

The second approach for the generation of mutant-killing test cases is a (guided)
generation of traces directly from the Circus specification. The traces are then con-

\footnote{Available at: \url{http://czt.sourceforge.net/latex/circus/circus-guide.pdf} accessed: Dec/13/2015.}
Table 2: Analysis of generated mutants for Chrono

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Operator</th>
<th>Mutants</th>
<th>Killed by FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ped</td>
<td>Event Drop</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>per</td>
<td>Event Replacement</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>pei</td>
<td>Event Insert</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>pco</td>
<td>Choice Operator</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ppoSeqPar</td>
<td>Sequential Composition</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ppoSeqInt</td>
<td>Interleave</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pmr</td>
<td>Message Replacement</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>pci</td>
<td>Communication Insert</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pce</td>
<td>Communication Elimination</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pprSchema</td>
<td>Schema Name</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>eniGuard</td>
<td>Guard Negation</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>eld</td>
<td>Operand Replacement</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>ear</td>
<td>Operator Replacement</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>eur</td>
<td>Unary Insertion</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>eak</td>
<td>Add k to Operand</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>esk</td>
<td>Sub k from Operand</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ead</td>
<td>Operand Replacement</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>err</td>
<td>Operator Replacement</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

5.1. Test generation via CSP and FDR

This approach is applicable only to Circus specifications with simple data models that can be directly encoded in CSP without further refinement. It has been, in any case, very useful to validate our ideas and approach. We discuss below the translation from Circus to CSP and the test-generation technique.

5.1.1. Translating Circus specifications into CSP

As shown in [54], a subset of Circus can be automatically translated to CSP; the main challenge is complex Z specifications. To carry out the experiments reported here and validate our approach to testing, however, we have carried out translation by hand.

To work with FDR, the specifications must be translated into the machine readable dialect of CSP [55] following the guidelines below:

- Channels and types are kept;
- The state components are encapsuled into a single data type with constructor AState, and passed as parameter to all processes and functions;
- A Circus action is translated into a CSP process;
- A reference to a schema s in an action A is unfolded to an intermediary process A_s(s(AState));
• Loops are translated as tail recursive calls;

• State changes defined by Z operations are performed by CSP functions from \( \text{AState} \) to \( \text{AState} \).

**Example 6.** For instance, Figure [13] shows the translation of Chrono. The \( \text{AInit} \), \( \text{IncSec} \) and \( \text{IncMin} \) Circus schemas are translated to the \( \text{ainit} \), \( \text{incsec} \) and \( \text{incmin} \) functions. Arguments and results of these functions are yielded by the type constructor \( \text{AState} \), encapsulating values for the two state components \( \text{sec} \) and \( \text{min} \). The anonymous main action of Chrono is translated into the \( \text{CHRONO} \) CSP process. The initialisation is captured by the parameter of the call to process \( \text{RUN} \). The loop is captured by parameterised recursive calls at the end of each choice of \( \text{RUN} \). The references to the schemas \( \text{IncSec} \) and \( \text{IncMin} \) inside the \( \text{Run} \) action are unfolded into the sub-process \( \text{RUN}_{\text{incsec}} \) and \( \text{RUN}_{\text{incsec incmin}} \).

5.1.2. Using FDR for fault-based test-case generation

In Section 3 we have explained that counterexamples yielded by a refinement check of a mutant against the original specification provide bases to build tests to kill the mutant. Figure [14] shows the output of FDR for the check \( \text{CHRONO} \sqsubseteq \text{F MCHRONO} \) for failures refinement in the context of the definitions in Figure [13]. It defines the following trace \( s \), forbidden continuation \( a \), and acceptance set \( X \).

\[
\begin{align*}
  s &= \langle \text{tick, time} \rangle \quad a = \text{out.1.1} \quad X = \{ \text{out.0.1} \}
\end{align*}
\]

For this experiment, the production of a counterexample gives rise to our account of the mutant as killed in Table 2. As stated in Theorem 1, finding such counterexamples is enough to assure that \( \text{MCHRONO} \) is a mutant of interest: it gives us the necessary elements to build a test case for, at least, the failures fault-based set.

In the particular example of the \( \text{CHRONO} \sqsubseteq \text{F MCHRONO} \) analysis, we have both a failure and a forbidden continuation, allowing the construction of one test for each of the \( \text{FBTests}_{\text{T}}^{\text{CHRONO(MCHRONO)}} \) and \( \text{FBTests}_{\text{F}}^{\text{CHRONO(MCHRONO)}} \) sets. Such tests are constructed using the \( T_{\text{T}} \) and \( T_{\text{F}} \) functions.

\[
\begin{align*}
  T_{\text{T}}(s, a) &= \text{inc} \rightarrow \text{tick} \rightarrow \text{inc} \rightarrow \text{time} \rightarrow \text{pass} \rightarrow \text{out.1.1} \rightarrow \text{fail} \rightarrow \text{Stop} \\
  T_{\text{F}}(s, X) &= \text{inc} \rightarrow \text{tick} \rightarrow \text{fail} \rightarrow \text{time} \rightarrow \text{fail} \rightarrow \text{out.0.1} \rightarrow \text{pass} \rightarrow \text{Stop}
\end{align*}
\]

In the traces of the execution of a parallel composition between the mutant \( \text{MCHRONO} \) and any of these tests the last verdict event is \( \text{fail} \), thus the tests kill the mutant.

All mutants generated for Chrono (in Figure 1) have been translated to CSP and analysed with FDR. As shown in Table 2, only two of the mutants are not of interest. Both are generated by the relational operator replacement \( \text{err} \), and are in Figure [15]. The changes introduced by \( \text{err} \) in both \( \text{ChronoErrEquiv1} \) and \( \text{ChronoErrEquiv2} \) occur in the expressions guarding the external choice between \( \text{IncMin} \) and \( \text{Skip} \). In \( \text{ChronoErrEquiv1} \), the original guard (\( \text{sec} = 0 \)) is replaced with (\( \text{sec} \leq 0 \)), and for \( \text{ChronoErrEquiv2} \), the guard (\( \text{sec} \neq 0 \)) is replaced with (\( \text{sec} > 0 \)). Both changes cause no observable effect, since \( \text{Range} \) imposed lower boundary to \( \text{sec} \) is 0.
The chronometer in CSP

-- Type and channels declaration
Range = {0..59}
channel tick, time
channel out:Range.Range

-- State simulation with single data type
Minsec = {(min,sec) | min <- Range, sec <- Range}
datatype Clock = AState.Minsec

-- AInit schema translation: state initialization min=0 and sec=0
ainit() = AState.(0,0)

-- IncSec schema translation: increments sec by one within Range
incsec(AState.(min,sec)) = AState.(min,(sec+1)%60)

-- IncMin schema translation: increments min by one within Range
incmin(AState.(min,sec)) = AState.((min+1)%60,sec)

-- Anonymous action to RUN process, with ainit state initialization
CHRONO = RUN(ainit())

-- Run action translation, stateful loop achieved using recursion
RUN(AState.(min,sec)) =
    tick -> RUN_incsec(incsec(AState.(min,sec)))
    []
    time -> out.min.sec -> RUN(AState.(min,sec))

-- Run sub-process translation, applying incsec function
RUN_incsec(AState.(min,sec)) =
    (sec == 0) & RUN_incsec_incmin(incmin(AState.(min,sec)))
    []
    (sec != 0) & RUN(AState.(min,sec))

RUN_incsec_incmin(AState.(min,sec)) = RUN(AState.(min,sec));

-- First mutant generated with eniGuard operator
MCHRONO = MRUN(ainit())

MRUN(AState.(min,sec)) =
    tick -> MRUN_incsec(incsec(AState.(min,sec)))
    []
    time -> out.min.sec -> MRUN(AState.(min,sec))

MRUN_incsec(AState.(min,sec)) =
    -- Negated guard mutation introduced below
    (not sec == 0) & MRUN_incsec_incmin(incmin(AState.(min,sec)))
    []
    (sec != 0) & MRUN(AState.(min,sec))
MRUN_incsec_incmin(AState.(min,sec)) = MRUN(AState.(min,sec));
Result: Failed
Visited States: 7
Visited Transitions: 17
Visited Plys: 2
Estimated Total Storage: 67MB
Counterexample (Trace Counterexample)
  Specification Debug:
    Trace: <tick, time>
    Available Events: \{out.0.1\}
  Implementation Debug:
    MRUN(AState.(0, 0)) (Trace Behaviour):
      Trace: <tick, time>
      Error Event: out.1.1

Figure 14: FDR output for \( CHRONO \subseteq_F MCHRONO \)

5.2. Test Generation from Circus specifications

The generation of tests from Circus specifications has been investigated and automated in the CirTA tool \[56, 57\], which uses an exhaustive approach to collect cstraces, along with their symbolic forbidden continuations and minimal acceptance sets, and enriches them with \textit{inc}, \textit{pass} and \textit{fail} verdict events. Since in that work there is no selection based on the text of the specification, there is no need for specification traces.

As explained in Section 3, for generating mutant-killing test cases, a first selection step of relevant specification traces is needed. The mutant (or, more precisely, the part where it differs from the specification) serves as a guide for the collection of these traces. In this section, we elaborate on this idea, proposing a chain of tools for test generation following the approach sketched at the end of Section 3.

Figure 16 depicts our proposed tool chain. In the first step, the specification, the mutation point, and the mutant are provided as input to a specification-trace generator (SpTG), which derives specification traces using a guided symbolic execution of the mutant. The aim is to generate relevant specification traces, as defined in Section 3.4.

For that, techniques of slicing can be used, similar to what is done for program analysis \[58\] and communicating automata specifications \[59\]. A generator based on the transition system that characterises specification traces is under development. The slicer and the check with respect to the original specification are the next steps.

We note that, instead of producing linear traces, the symbolic execution can easily be adapted for producing some symbolic execution tree. Such a tree can be the basis of tree-shaped tests, which avoid inconclusive verdicts by relaxing the constraint introduced by linear tests, that the SUT must follow one expected trace: the SUT can choose among the correct traces embedded in the tree. Such a factorization of linear tests, as discussed in \[41\], has the advantage of decreasing both the number of tests and the number of inconclusive verdicts, but the drawback that it leaves some control to the SUT with the risk that some relevant traces are not attempted.
process ChronoErrEquiv1 ≡
...
Run ≡ (tick → IncSec; ((sec ≤ 0) & IncMin)
□((sec ≠ 0) & Skip)))
□(time → out !(min, sec) → Skip)
• (AInit; (µ X • (Run; X)))

process ChronoErrEquiv2 ≡
...
Run ≡ (tick → IncSec; ((sec = 0) & IncMin)
□((sec > 0) & Skip)))
□(time → out !(min, sec) → Skip)
• (AInit; (µ X • (Run; X)))

Figure 15: Two equivalent mutants of Chrono exposed by FDR

In a second step, the set of specification traces are given as input to a cstrace generator (CsTG). Each specification trace is converted into one cstrace. A constructive conversion procedure is formally specified in [28]. As explained in Section 3, it is based on an operational semantics that characterises the behavior of the path of a Circus specification identified by the labels of a specification trace. As can be expected, since the events, guards, and actions identified in specification traces are components of Circus actions, the operational semantics used in the conversion is very similar to a restricted subset of the Circus semantics. The automation of the conversion is, therefore, similar to the component of SpTG that calculates specification traces.

A prototype tool for proving (or disproving) refinements of Circus specifications, Isabelle/Circus, is presented in [60]. For each translated cstrace, CsTG checks whether it is a new cstrace or if it introduces any new deadlock, using Isabelle/Circus and reusing some components of the CirT A tool; if not, the cstrace is also discarded. CsTG

yields a set of cstraces with their symbolic forbidden continuations and acceptance
sets. Each cstrace is converted (by SyTG) into a symbolic test by adding the verdicts at
the appropriate points. These symbolic tests are adequately instantiated using an SMT
solver as reported and illustrated in [57]. An example is given in Section 6.

The tool chain is expected to work using a lazy scheme, that is, a computation is
only performed when its result is required. Thus, we avoid generating infinite sets of
specification traces and cstraces, with, when necessary, some limitation on the length
of the considered specification traces or cstraces.

The classical undecidable problem of equivalent mutants of programs [61] arises
here under the form of checking whether a Circus model is a refinement of another one.

For such a rich specification language, the use of a powerful proof assistant is unavoid-
able. The prototype Isabelle/Circus environment [60] is based upon the Isabelle/HOL
proof environment where theories and rules of Circus semantics and refinement have
been embedded. Once enriched with efficient dedicated proof tactics, it can be used
both for a preliminary refinement check for test generation and for rejection of those
cstraces that are cstraces of the original specification.

Our efforts are now focused in prototyping the necessary parts of the tool chain
for automating the described strategy. The most complex and challenging tool is the
SpTG, whose implementation starts to yield some preliminary results for a small subset
of the Circus operational semantics. Considering the established theory background,
it is a matter of time to achieve an operational level, allowing us to shift our concerns
into issues of optimization and scalability.

6. Cash Machine: Another example

In this section, we illustrate how the approach we propose can be used for guiding
test generation, using a more complex Circus specification as an example. We con-
sider several mutant operators and the respective mutants, and discuss some interesting
characteristics of the process of analysing them and generating the killer tests.

Figure 17 presents a slightly modified version of the cash-machine example used
in [28]. First of all, we declare the set $CARD$ of valid cards. Next, we declare some
channels. Requests for money are accepted by the cash machine through the channel
$inc$, which takes a card and the amount to be withdrawn. The amount is a positive
natural number. Cards are returned through a channel $outc$. The notes in and dispensed
by the cash machine are those whose denominations are in the set $Note$. For simplicity,
we consider just a few notes, and do not address the fact that the amount requested
must be decomposable in terms of the notes available. If it is not, the machine fails
to dispense the cash. In our model, cash is represented as a bag of notes: elements
of the set $Cash$. If there is enough money in the machine and a way of providing the
requested amount, the cash is output through a channel $cash$. The channel $refill$ is used
to request the note bank of the cash machine to be refilled.

The cash machine accepts requests for cash and decides whether the cash should
be dispensed. The only state component of $CashMachine$ is a function $nBank$ that
records, for each denomination, the amount of notes available. The state is defined by
a schema, $CMState$, which declares $nBank$ as a total function.
\[
[\text{CARD}]
\]
\text{channel} \quad inc : \text{CARD} \times \mathbb{N}_1; \quad outc : \text{CARD}; \quad cash : \text{Cash}; \quad refill \\\n\text{Note} = [10, 20, 50] \\\n\text{Cash} = \text{bag Note} \\\n\text{process} \quad \text{CashMachine} \triangleq \text{begin} \\\n\text{state} \quad \text{CMState} = [n\text{Bank} : \text{Note} \rightarrow 0 \ldots \text{cap}] \\\n\begin{align*}
\Delta \text{CMState} \\
a? : \mathbb{N}_1 \\
notes! : \text{Cash} \\
\Sigma \text{notes!} = a? \\
\forall n : \text{Note} \bullet (\text{notes!} \# n) \leq n\text{Bank} n \land n\text{Bank’} n = (n\text{Bank} n) - (\text{notes!} \# n)
\end{align*} \\
\text{DispenseNotes} \quad \text{DispenseError} \\
\text{Dispense} = \text{DispenseNotes} \lor \text{DispenseError} \\
\begin{cases}
inc?c?a \rightarrow \\
\text{outc!c} \rightarrow X \\
\var \text{notes} : \text{Cash} \bullet \\
\begin{cases}
\text{Dispense}; \\
(\text{notes} \# [] \land \text{Cash!notes} \rightarrow \text{Skip}) \\
(\text{notes} = [] \land \text{Skip}
\end{cases} \; \text{; outc!c} \rightarrow X \\
\end{cases} \\
\text{refill} \rightarrow n\text{Bank} := \{10 \leftrightarrow \text{cap}, 20 \leftrightarrow \text{cap}, 50 \leftrightarrow \text{cap}\} ; \; X
\end{cases}
\]

Figure 17: Cash machine specification
Table 3: Count of mutants generated for CashMachine.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Operator</th>
<th>Mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>ped</td>
<td>Event Drop</td>
<td>1</td>
</tr>
<tr>
<td>pei</td>
<td>Event Insert</td>
<td>1</td>
</tr>
<tr>
<td>pco</td>
<td>Choice Operator</td>
<td>2</td>
</tr>
<tr>
<td>ppeoSeqPar</td>
<td>Sequential Composition</td>
<td>3</td>
</tr>
<tr>
<td>ppeoSeqInt</td>
<td>Interleave</td>
<td>3</td>
</tr>
<tr>
<td>pci</td>
<td>Communication Insert</td>
<td>4</td>
</tr>
<tr>
<td>pce</td>
<td>Communication Elimination</td>
<td>4</td>
</tr>
<tr>
<td>pprSchema</td>
<td>Schema Name</td>
<td>2</td>
</tr>
<tr>
<td>eni</td>
<td>Negation Insert</td>
<td>6</td>
</tr>
<tr>
<td>eniGuard</td>
<td>Guard Negation</td>
<td>2</td>
</tr>
<tr>
<td>elr</td>
<td>Operator Replacement</td>
<td>3</td>
</tr>
<tr>
<td>eld</td>
<td>Operand Replacement</td>
<td>16</td>
</tr>
<tr>
<td>ear</td>
<td>Operator Replacement</td>
<td>3</td>
</tr>
<tr>
<td>eur</td>
<td>Unary Insert</td>
<td>1</td>
</tr>
<tr>
<td>eak</td>
<td>Add k to Operand</td>
<td>8</td>
</tr>
<tr>
<td>esk</td>
<td>Sub k from Operand</td>
<td>8</td>
</tr>
<tr>
<td>ead</td>
<td>Operand Replacement</td>
<td>6</td>
</tr>
<tr>
<td>err</td>
<td>Operator Replacement</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3: Count of mutants generated for CashMachine.

The \textit{DispenseNotes} data operation takes an amount \(a\) as input and produces a bag of notes \(\text{notes!}\) as output; it also updates \(nBank\). It is defined using a \(Z\) schema that specifies a relation on \(CMState\). The value of \(\text{notes!}\) is nondeterministically chosen: it is any bag \(\text{notes!}\) whose sum \(\sum \text{notes!}\) of its elements is equal to \(a\), and such that, for each note denomination \(n\), the number \(\text{notes!} \# n\) of occurrences of \(n\) is less than or equal to the number \(n\text{Bank} n\) of notes of denomination \(n\) in the bank.

If there is no such bag, we have an error: the output is the empty bag \([[]]\), and the state is not changed. This is defined by the schema \(\text{DispenseError}\). The total operation to \textit{Dispense cash} is the schema disjunction of \textit{DispenseNotes} and \textit{DispenseError}.

The main action of \textit{CashMachine} defines that it accepts a request \(\text{inc}?c?a\); this is an input of any card \(c\) and any amount \(a\). It then decides whether to output the card using \text{outc} and no money, or dispense the requested amount using \text{cash}. The decision is nondeterministic; it is defined by factors outside of this model: status of the card, balance on the corresponding account, and so on. The cash machine also accepts requests to \text{refill} the note bank. A recursion offers these choices over and over again.

We have used our mutant-generation prototype for the \textit{CashMachine} example. The resulting numbers are shown in Table 3. We consider some mutations below.

6.1. Communication elimination (\(pce\)) of the first occurrence of \textit{outc}!c

We consider first the mutant obtained by applying the \(pce\) operator to remove the first occurrence of \textit{outc}!c. We call \textit{MutatedCashMachine'} the resulting process. Among its specification traces that reach the mutation point, there are \(<\text{inc}?c?a, \text{refill}>\)
and \((inc?c?a, inc?c?a)\). The corresponding cstraces are shown below.

\[
\begin{align*}
((inc?a_9?a_4, refill), & a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1) \\
((inc?a_9?a_4, inc?a_2?a_3), & a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1 \land a_2 \in \text{CARD} \land a_3 \in \mathbb{N}_1)
\end{align*}
\]

They are not cstraces of \textit{CashMachine}, and so these traces of \textit{MutatedCashMachine}'
are relevant for testing against traces refinement. The test generation can be done via
the selection of one of the specification traces above, its translation into its ctrace, and
the construction of the corresponding symbolic test. For the second one we have:

\[
\begin{align*}
inc & \rightarrow inc?a_0?a_1 : (a_0 \in \text{CARD} \land a_1 \in \mathbb{N}_1) \rightarrow \text{pass} \rightarrow \\
inc?a_2?a_3 : & (a_2 \in \text{CARD} \land a_3 \in \mathbb{N}_1) \rightarrow \text{fail} \rightarrow \text{Stop}
\end{align*}
\]

By resolution of the constraints on \(a_0, a_1, a_2, a_3\), choosing cards \(a_0\) and \(a_2\), and amounts
\(a_1\) and \(a_3\), we can obtain a concrete test that kills \textit{MutatedCashMachine}'.

6.2. Communication elimination (pce) of the second occurrence of \textit{outc!c}

When removing the second occurrence of the \textit{outc!c} event, the following specification traces appear, that reach the mutation point:

\[
\begin{align*}
\langle inc?c?a, var \text{notes}, Dispense, notes \neq \| \rangle, & cash!\text{notes, Skip, inc?c?a} \\
\langle inc?c?a, var \text{notes}, Dispense, notes \neq \| \rangle, & cash!\text{notes, Skip, refill} \\
\langle inc?c?a, var \text{notes}, Dispense, notes = \| \rangle, & \text{Skip, inc?c?a} \\
\langle inc?c?a, var \text{notes}, Dispense, notes = \| \rangle, & \text{Skip, refill}
\end{align*}
\]

The corresponding cstraces are shown below.

\[
\begin{align*}
( & \langle inc?a_9?a_1, cash!a_2, inc?a_3?a_4 \rangle, \\
& a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1 \land a_2 \in \text{Cash} \land \Sigma a_2 = a_1 \land a_3 \in \text{CARD} \land a_4 \in \mathbb{N}_1) \\
( & \langle inc?a_9?a_1, cash!a_2, refill \rangle, \\
& a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1 \land a_2 \in \text{Cash} \land \Sigma a_2 = a_1) \\
( & \langle inc?a_9?a_1, inc?a_2?a_3 \rangle, a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1 \land a_2 \in \text{CARD} \land a_3 \in \mathbb{N}_1) \\
( & \langle inc?a_9?a_1, refill \rangle, a_9 \in \text{CARD} \land a_1 \in \mathbb{N}_1)
\end{align*}
\]

They are not cstraces of the original specification and can be used as bases for killer
tests. The last two cstraces are the same as those obtained when dealing with the
removal of the first occurrence of \textit{outc!c} in the previous section.

6.3. Substitution (ppr\text{Schema}) of the reference to \textit{Dispense} by \textit{DispenseError}

As another example, we consider the mutant obtained by the application of the
\textit{ppr\text{Schema}} operator to the second occurrence of the \textit{Dispense} schema name (that is, the
use of \textit{Dispense} in the variable block that declares \textit{notes} in the main action of the
process \textit{CashMachine} in Figure \[17\]. We can use \textit{ppr\text{Schema}} to replace \textit{Dispense}
with, for instance, \textit{DispenseError}, whose precondition may not hold.

The specification trace below reaches the mutation point.

\[
\langle inc?c?a, var \text{notes, DispenseError} \rangle
\]

It is a specification trace of the mutated specification because, in some cases, the pre-
condition of \textit{DispenseError} is satisfied: it depends on the initialisation of \textit{nBank}.

The corresponding cstrace is:

\[(\{\text{inc}?\alpha_0?\alpha_1\}, \alpha_0 \in \text{CARD} \land \alpha_1 \in \mathbb{N}_1)\]

It is a cstrace of the original specification, but after \textit{inc}?\alpha, the internal choice leads either to (\textit{outc}!c) or to \textit{DispenseError}. If the precondition of \textit{DispenseError} does not hold, it behaviour is divergent. Therefore, this mutant is discarded.

6.4. Insertion of event (\textit{pei}) \textit{refill}

The result of a mutation using \textit{pei} to duplicate the event \textit{refill} in the main action of \textit{CashMachine} is given in Figure[18]. It has new specification traces, like, for instance:

\[\langle \text{refill, refill, } n\text{Bank} := \{10 \mapsto \text{cap}, 20 \mapsto \text{cap}, 50 \mapsto \text{cap}\} \rangle\]

The corresponding cstrace is \langle\langle \text{refill, refill}\rangle, \text{True} \rangle, which is a cstrace of the original \textit{CashMachine} process. We observe the same situation for all the new specification traces: they are new because they embed the subtrace

\[\langle \ldots \text{refill, refill, } n\text{Bank} := \{10 \mapsto \text{cap}, 20 \mapsto \text{cap}, 50 \mapsto \text{cap}\} \ldots \rangle\]

or finish with a double occurrent of \textit{refill}. In the corresponding cstraces, these give rise to subtraces \langle\langle \ldots \text{refill, refill}\ldots \rangle, \ldots \rangle, which are admitted by \textit{CashMachine}. This means that the original and the mutated processes have the same traces, and we cannot distinguish them with a test for traces inclusion.

This mutant, however, has new failures. For example,

\[\langle \text{refill, } n\text{Bank} := \{10 \mapsto \text{cap}, 20 \mapsto \text{cap}, 50 \mapsto \text{cap}\}, \text{inc}?\alpha \rangle,\]

is a specification trace of \textit{CashMachine}, but not of the mutated process. After the trace \langle \text{refill} \rangle, the only accepted event of the mutated process is \textit{refill} and any instantiation.
of inc?c?a is refused. So, ⟨refill⟩ paired with a singleton set containing an event inc.c.a is a failure of the mutated process, but not of CashMachine. On the other hand, the singleton set is a minimal acceptance of CashMachine after ⟨refill⟩, and any instantiation of the symbolic test below is a killer test.

\[
\text{inc} \rightarrow \text{refill} \rightarrow \text{fail} \rightarrow \text{inc}\alpha_0\alpha_1 : (\alpha_0 \in \text{CARD} \land \alpha_1 \in \mathbb{N}_1) \rightarrow \text{pass} \rightarrow \text{Stop}
\]

Instantiation requires the choice of values for \(\alpha_0\) and \(\alpha_1\) that satisfy the given constraint.

### 6.5. Mutation of choice operator (pco)

A mutation of the external choice in the main action of CashMachine into an internal choice, using pco, gives rise to a situation similar to that of the previous section. As noted in Section 4, such a mutation does not introduce new specification traces. It can, however, introduce failures. For instance, refill may be refused after the empty trace by the mutated process, but not by CashMachine, which has a minimal acceptance \{refill\} after the empty trace. A killer test is fail → refill → pass → Stop.

### 6.6. Communication insert (pci)

The communication insert operator pci is similar to the event insert pei operator considered in the previous section. It is, however, applied to a communication instead of a synchronization. We consider here the duplication of cash!notes. A specification trace that reaches the mutation point is as follows.

\[
\langle \text{inc?c?a, var notes, Dispense, notes} \neq []], \text{cash!notes, cash!notes} \rangle
\]

The corresponding cstrace is

\[
(\langle \text{inc?c?a}_1, \text{cash!c}_2, \text{cash!c}_3), \\
\alpha_0 \in \text{CARD} \land \alpha_1 \in \mathbb{N}_1 \land \alpha_2 \in \text{Cash} \land \sum \alpha_2 = \alpha_1 \land \alpha_3 \in \text{Cash} \land \alpha_3 = \alpha_2)
\]

It is not a cstrace of CashMachine and leads to the symbolic test below.

\[
\text{inc} \rightarrow \text{inc?c}_0\alpha_1 : (\alpha_0 \in \text{CARD} \land \alpha_1 \in \mathbb{N}_1) \rightarrow \text{inc} \\
\text{cash!c}_2 : (\alpha_2 \in \text{Cash} \land \sum \alpha_2 = \alpha_1) \rightarrow \text{pass} \\
\text{cash!c}_3 : (\alpha_3 \in \text{Cash} \land \alpha_3 = \alpha_2) \rightarrow \text{fail} \rightarrow \text{Stop}
\]

Once the above test is instantiated, it yields a killer test.

### 6.7. Mutation of sequential compositions (ppoSeqPar)

The new parallel compositions introduced by ppoSeqPar synchronise on all channels in a given set CS and have no write access to any variables. In the main action of CashMachine, there are three sequential compositions. We show in Figure 19 the result of mutating the one insider the variable block that declares notes.

In this case, the mutated process may deadlock after Dispense. Both parallel actions act on the arbitrary initial value of notes. If that value is not the empty bag, since the synchronisation on cash required by the external choice cannot happen, because Dispense is not ready to communicate on cash, there is a deadlock. If, however, that
arbitrary initial value happens to be the empty bag, the mutated process does not deadlock. It dispenses the card via outc without changing the state, since the changes made by the parallel actions cannot be recorded in any variables. So, we have a fail safe.

The cstrace ((inc?α_0 ?α_1), α_0 ∈ CARD ∧ α_1 ∈ N_1) is associated with a set of symbolic acceptances including (outc!α_3, α_6 ∈ CARD ∧ α_1 ∈ N_1 ∧ α_3 = α_0) and (cash!α_3, α_6 ∈ CARD ∧ α_1 ∈ N_1 ∧ α_3 ∈ Cash ∧ Σα_3 = α_1). This is not an acceptance of the mutated process, and can be used to define a killer test.

\[
\begin{align*}
\mu X & \bullet\\
inc?c?α \rightarrow\\
& \text{outc!c} \rightarrow X\\
\square && \\
\var{\text{notes}} : \text{Cash} \bullet\\
& \text{Dispense}\\
& \left\{ \begin{array}{l}
(\text{inc}, \text{outc}, \text{cash}, \text{refill})\\
(\text{notes }\neq \emptyset) & \& \text{cash!notes} \rightarrow \text{Skip}\\
\square \\
(\text{notes }=\emptyset) & \& \text{Skip}
\end{array} \right.\\
\square && \\
\text{refill} \rightarrow nBank := \{ 10 \rightarrow \text{cap, 20 \rightarrow cap, 50 \rightarrow cap} \} ; X
\end{align*}
\]

Figure 19: Mutation of the first occurrence of ; by ppoSeqPar

Instantiation keeps the restrictions on the inputs and defines specific values for outputs. Above, the value of α_1 has different constraints in the outputs via outc and cash.

Based on the examples in this section, we note that the construction of test cases from mutants is a very challenging task, which demands the support of specialised tools. The tool support we discuss in Section 5 is paramount for making our approach practical and we are placing efforts in developing it with the aid of frameworks for symbolic manipulation and constraint solvers. In Appendix B, we include further examples of mutants for a Circus specification (of an Emergency Recovery System).

7. Related Work

Mutation has already been used for guiding test-case generation from (formal) models in many different pieces of work [52, 63, 64, 31, 56, 65, 66, 67, 68]. As already mentioned, it is also used to assess the quality of a test suite. The possibility of selecting on which errors to concentrate is a good mechanism to tackle the explosion of test cases (see [50] and [66] for recent surveys). A more general survey on the main developments of mutation testing is found in [69].
Budd and Gopal [70] have pioneered the investigation on testing by mutating specifications. They propose the use of a mutant of a specification to generate tests for programs. Specifications are based on predicate calculus. The mutant is a variation of a predicate defining the expected behavior of the program. A test case is an input for which the original specification and the mutant produce different truth values.

Ammann et al. [71] use the SMV model checker to generate test cases from mutants of a specification. The mutant operators are defined at the syntactical level, and the test cases are traces of the specification but not of the mutant. The application of a similar approach to an industrial case study is reported in [72]. Simulink models are mutated and the test cases are generated with CBMC (bounded model checker for C). Generation of tests from mutated Simulink models is also investigated in [74].

The work of Papadakis et al. [74, 75, 76] automates white-box test-case generation for programs, relying on symbolic and concolic execution, mutant schemata and the weak mutation-testing criterion. The goals are to lower the cost of test-case generation and increase the quality of the obtained test suite.

Mutation testing has also been used to generate test cases for security-critical systems in [63]. The mutants are used to model vulnerabilities. A constraint solver is employed to find a trace of the mutant that does not satisfy the security properties of the system. If such a trace exists, the mutant introduces a vulnerability and the test case shows how to exploit it. This approach is similar to ours, but due to the nature of the model we use, refinement verification is employed instead of a constraint solver. Similarly, the work by John Clark et al. [31], whose mutant operators we have considered in Section 4, uses mutation testing for checking system security. Moreover, Clark et al. use the mutants to validate the specification, while we use them to generate tests.

Krenn and Aichernig [64] mutate program contracts and use the SAT solvers Boogie and Z3 to generate test cases for Spec# models. Their proposed technique automatically generate tests that can distinguish whether an implementation refines a faulty specification. We use mutants to select tests from our fault-based exhaustive test sets.

Aichernig and colleagues have advanced the application of mutation testing for models in various formalisms [56, 65, 62, 66]. A test case is seen as an abstraction (according to a traces-refinement relation) of the specification, that is, an implementation (or specification) should refine the test case if it passes the test. Thus, test-case synthesis is a reverse refinement problem. Mutants guide the generation of test cases; a fault detecting test case is an abstraction of the specification, but not of the mutant. The theory is developed in the context of Hoare and He’s UTP [19]. Mutants are generated both for the specification and the implementation. Our approach is on the same vein of Aichernig and colleagues’ work, extending the main concepts to a new formalism.

8. Conclusions and future work

We have formally defined mutation testing for Circus by characterising (1) the exhaustive sets of tests that can kill a given mutant, considering both traces refinement and conf, that is, process refinement in Circus as a whole; (2) a technique to select tests from these sets based on specification traces of the mutants; and (3) an extensive collection of operators to generate mutants considering faults related to both reactive
and data manipulation behaviour. Like the Circus testing theory, this work is of general relevance for state-rich algebras for refinement.

To make our ideas concrete, we have led some preliminary experimentation on models that are both simple enough (regarding its data structures) and finite to enable model checking via FDR. We have also developed a first tool in Java for mutant generation, which is the front-end both for using FDR and for a chain of tools we have defined for mutants analysis and killer-tests generation. The mutant analysis can make use of the Isabelle Circus refinement checker, and the test generation can use some components of the exhaustive test generator CirTA.

We, however, are not in a position to provide experimental results that address scalability, since the tool chain we have available so far is not suitable for conducting such studies. The main bottleneck we foresee is the cost of the symbolic manipulation of the model, which we expect to tackle using slicing techniques. Another issue is related to decidability problems regarding the identification of useless mutants, namely, those that refine the original model. We have not addressed this yet, but will in the future steps of our research using model checking and automated theorem proving.

Given a mutation operator such as one of those given in Section 4, it is attractive to avoid constructing the mutants to generate the tests to kill them as described above. For that, we need a way of calculating the traces and failures of the mutants without constructing them. This calculation could take advantage of the knowledge of traces and failures of the original process, but the effect of the mutation operators on the semantics of a process is not direct. More precisely, the semantic models of interest are not a congruence for the mutant operators. This gives rise to an interesting challenge.

Generally, mutations are syntactic changes. Since our specification traces are close to the syntax of the specifications, it may well be the case that they do provide an adequate way to construct traces of the mutants in terms of those of the original specification. An analysis of mutation operators for specification traces and their relation to our operators is an interesting avenue for future work.

We also plan to investigate “semantic mutations”. The idea is to consider the sets of traces and failures of the specification and to study mutations of these sets. This will avoid the construction of the syntactic mutants. It is important to note that the mutations must preserve the properties of the sets, for instance, the set of traces is prefix-closed, and the set of failures is subset-closed with respect to refusal sets.

Acknowledgments

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Appendix A. Circus operational semantics

We reproduce here part of the Circus operational semantics as presented in [45].

As already said, as usual, the operational semantics of Circus is based on a transition relation that associates configurations. For processes, the configurations are processes themselves. For actions, they are triples as explained in Section 2.1.
To give the operational semantics of a process, we use a novel construct to define a process. It records the current local state using a constraint and a state assignment. The first transition rule for processes below introduces the record of the local state using a (list of) fresh symbolic variable(s) \( \omega_0 \). The constraint defines that \( \omega_0 \) is (are) of the appropriate type(s), and in the state assignment \( \omega_0 \) is assigned to the state component(s) \( x \). In all rules, the symbolic variables introduced are assumed to be fresh.

\[
\begin{align*}
\text{begin} & \quad \text{state}[x:T] \\
\bullet A & \quad \text{end} \\
\end{align*}
\]

\[
\xi
\begin{align*}
\text{begin} & \quad \text{state}[x:T] \mid \text{loc}(\omega_0 \in T \mid x := \omega_0) \\
\bullet A & \quad \text{end} \\
\end{align*}
\]

(A.1)

The second transition rule for processes, which we omit here for conciseness, applies to the extended form of a basic process. The rule allows a process to evolve in accordance with the evolution of its main action in the state defined by the \( \text{loc} \) clause. We, therefore, focus in the sequel on the transition relation for actions.

The evolution of an output prefixing \( \text{d!e} \rightarrow A \) is labelled. The label \( \text{d!e} \) involves the fresh constant \( \omega_0 \); the new constraint defines its value to be that of \( e \) in the current state \( s \). The remaining action to be executed is \( A \).

\[
c \quad \begin{align*}
\text{(c } s \vdash \text{d!e} \rightarrow A) & \quad \rightarrow (c \land (s; \omega_0 = e) \mid s \vdash A)
\end{align*}
\]

(A.2)

The transition rule for an input prefixing \( \text{d?x} \rightarrow A \) is as follows.

\[
c \land T \neq \emptyset \quad x \notin \alpha_s
\]

\[
(c \mid s \vdash \text{d?x} : T \rightarrow A) \rightarrow (c \land \omega_0 \in T \mid s; \text{var x} := \omega_0 \vdash \text{let x } \bullet A)
\]

(A.3)

The label is \( \text{d?}\omega_0 \). In the new the state, \( x \) is declared and assigned \( \omega_0 \). The only restriction on \( \omega_0 \) is that it has the same type as \( d \). The remaining action \( \text{let x } \bullet A \) records the fact that \( x \) is in scope in \( A \) as a local variable. The construct \( \text{let x } \bullet A \) has been introduced specifically for use in the operational semantics. When \( A \) terminates, a rule for \( \text{let x } \bullet \text{Skip} \) closes the scope of \( x \) in the state and removes the \( \text{let x} \) declaration.

For an internal choice \( A_1 \cap A_2 \), silent transitions are available to either \( A_1 \) or \( A_2 \) (in a configuration with the same constraint and state assignment).

\[
c \quad \begin{align*}
\text{(c } s \vdash A_1 \cap A_2) & \quad \rightarrow (c \mid s \vdash A_1)
\end{align*}
\]

\[
c \quad \begin{align*}
\text{(c } s \vdash A_1 \cap A_2) & \quad \rightarrow (c \mid s \vdash A_2)
\end{align*}
\]

(A.4)

The treatment of parallelism is more subtle. We introduce a new form of action \( \text{par} s \mid x \bullet A \) to record a local state \( s \) of the parallel action \( A \), with write control over the variables in \( x \). The first transition rule for a parallelism defines a silent transition that rewrites it in terms of this new construct.

The rule below allows evolutions of the first parallel action \( A_1 \) that are either silent or do not involve a channel in the synchronisation set to be reflected in the parallelism.
A similar omitted rule considers independent evolutions of $A_2$.

\[
(c \mid s_1 \models A_1) \xrightarrow{1} (c_2 \mid s_3 \models A_3) \quad 1 = e \lor \text{c}_{\text{hs}} \notin \text{c}_{\text{s}}
\]

\[
\begin{align*}
(c \mid s) &\models \begin{cases}
(\text{par} s_1 \mid x_1 \cdot A_1) \\
[\text{c}_{\text{s}}]
\end{cases} \quad (c_3 \mid s) &\models \begin{cases}
(\text{par} s_3 \mid x_1 \cdot A_3) \\
[\text{c}_{\text{s}}]
\end{cases}
\end{align*}
\]

(A.5)

The next rule is for when the parallel actions can evolve by synchronising. In particular, $A_1$ can carry out an input $d!w_1$, and $A_2$ an output $d!w_2$, where $d$ is a channel in the synchronisation set, and the values communicated are equal. The transition rule establishes that, in this case, the parallelism as a whole actually performs an output. The new constraint records the restriction that $w_1 = w_2$.

\[
(c \mid s_1 \models A_1) \xrightarrow{d!w_2} (c_2 \mid s_3 \models A_3) \quad (c \mid s_2 \models A_2) \xrightarrow{d!w_2} (c_4 \mid s_4 \models A_4)
\]

\[
\begin{align*}
(c \mid s) &\models \begin{cases}
(\text{par} s_1 \mid x_1 \cdot A_1) \\
[\text{c}_{\text{s}}]
\end{cases} \quad (c_3 \mid c_4 \land w_1 = w_2 \mid s) &\models \begin{cases}
(\text{par} s_3 \mid x_1 \cdot A_1) \\
[\text{c}_{\text{s}}]
\end{cases}
\end{align*}
\]

(A.6)

Similar rules apply when $A_1$ can output and $A_2$ input, or when both $A_1$ and $A_2$ can output. When they can both input, the parallelism also performs an input.

Perhaps the most interesting rule is the one that applies when both parallel actions have terminated. In this case, the parallelism terminates.

\[
(c \mid s) \models \begin{cases}
(\text{par} s_1 \mid x_1 \cdot \text{Skip}) \\
[\text{c}_{\text{s}}]
\end{cases} \quad (c \mid (\exists x' \mid s_1) \land (\exists x' \mid s_2) \models \text{Skip})
\]

(A.7)

The state after the parallelism is defined by composing the local states of the parallel actions. We keep from the local state $s_1$ of the first action only the changes to the variables in its name set $x_1$. This is achieved by hiding (quantifying) the final value of the variables in the complement set $x_2$. The same applies to $s_2$. The conjunction of the quantifications defines the new state. We observe that, alternatively, we can define the new state as $s_1 \models \text{end} x_2 \land s_2 \models \text{end} x_1$.

Rules for external choice require similar considerations. Actions in an external choice can evolve independently, with local access to all variables, until the choice is made, and consequently, the local changes become global. The new form of action $(\text{loc} c \mid s \cdot A_1) \equiv (\text{loc} c \mid s \cdot A_2)$ records the initial state locally.

\[
(c \mid s \models A_1 \land A_2) \xrightarrow{c} (c \mid s \models (\text{loc} c \mid s \cdot A_1) \equiv (\text{loc} c \mid s \cdot A_2))
\]

(A.8)
An event, however, does resolve the choice.

\[
\begin{align*}
\frac{c_1}{(c | s \models (\text{loc } c_1 | s_1 \cdot \text{Skip}) \oplus (\text{loc } c_2 | s_2 \cdot A)) \xrightarrow{\text{ts}} (c_1 | s_1 \models \text{Skip})} \\
\end{align*}
\]

(A.9)

Since external choice is commutative, similar rules apply for each of the actions in the choice. We present just one of the two rules in each case. The next rule establishes that silent transitions do not resolve the choice.

\[
\begin{align*}
(c_1 | s_1 \models A_1) \xrightarrow{\text{ts}} (c_3 | s_3 \models A_3)
\end{align*}
\]

(A.10)

An event, however, does resolve the choice.

\[
\begin{align*}
\frac{(c_1 | s_1 \models A_1) \xrightarrow{1} (c_1 | s_3 \models A_3) \quad 1 \neq \epsilon}{(c | s \models (\text{loc } c_1 | s_1 \cdot A_1) \oplus (\text{loc } c_2 | s_2 \cdot A_2)) \xrightarrow{1} (c_3 | s_3 \models A_1)}
\end{align*}
\]

(A.11)

For a hiding \( A_1 \ \text{c} \text{ } c_1 \), the rules allow evolution of \( A_1 \) to lead to evolution of the hiding itself. In the rule below, evolution does not involve a hidden channel, so the label for the hiding transition is that for the \( A_1 \) transition.

\[
\begin{align*}
\frac{(c_1 | s_1 \models A_1) \xrightarrow{1} (c_2 | s_2 \models A_2) \quad \text{chan } l \notin c_1}{(c_1 | s_1 \models A_1 \ \text{c} \text{ } c_1 \) \xrightarrow{1} (c_2 | s_2 \models A_2 \ \text{c} \text{ } c_1)}
\end{align*}
\]

(A.12)

If, on the other hand, \( A_1 \) can communicate on a hidden channel, the corresponding evolution of the hiding is silent.

\[
\begin{align*}
\frac{(c_1 | s_1 \models A_1) \xrightarrow{1} (c_2 | s_2 \models A_2) \quad \text{1 = } \epsilon \vee \text{chan } l \in c_1}{(c_1 | s_1 \models A_1 \ \text{c} \text{ } c_1 \) \xrightarrow{1} (c_2 | s_2 \models A_2 \ \text{c} \text{ } c_1)}
\end{align*}
\]

(A.13)

An omitted rule specifies that if \( A_1 \) terminates, so does the hiding.

**Appendix B. Emergency Response System**

In this appendix, we include another example to illustrate the approach proposed in this paper. We consider the Emergency Response System (ERS), introduced in \[77\].

Targets, that is, incidents requiring emergency response, are identified by callers, that is, members of the public, using the ERS and a set of operationally independent sub-systems, such as Phone System, Radio System, Call Center, and Emergency Response.
Unit (ERU). The ERS must ensure that every call should be sent to the correct target. More details about the ERS can be found in [78]. It is used in [52] to assess the deadlock detection of a prototype model checker for Circus.

The Circus specification in Figure B.20 models a subset of the ERU, focusing on the behavior of an emergency response unit manager, specified by the process $ERU$, and of a caller, process $InitiateRescueOrFault$. The latter sends rescue service requests to the $ERU$ and can trigger a message-drop fault, to be detected and treated by a fault-recovery component, specified by a process $Recovery$ omitted here.

All three processes run concurrently and synchronise on the sets of channels indicated in the definition of their parallel composition. In broad terms, the $ERU$ process manages the amount of available and allocated response units. $InitiateRescueOrFault$ asks for idle units and the $ERU$ allocates them accordingly. If a fault is triggered, $Recovery$ logs the occurrence and resend the dropped message to the manager.

This example illustrates mutations that may affect concurrency. The operators $ppoParSeq$ and $ppoParInt$ are applicable in this context and yield interesting results that we discuss in the following sections.

Appendix B.1. Mutations by $ppoParInt$

The mutation operator $ppoParInt$ replaces a parallel composition with an inter-leaving, causing the concurrent execution to take place without synchronization between the processes. For this example, this operator can be applied in both parallel compositions to yield the mutants shown in Figure B.21.

Both mutants can be killed by test cases based on the fact that the minimal acceptance set for the original $ERSystem$ after the empty trace contains only the event $start\_rescue$. Other events available due to the mutation are forbidden continuations. The test cases $T_T(s, a_1)$ and $T_F(s, X)$ below are based on the empty trace $s = \langle \rangle$, forbidden continuation $a_1 = start\_recovery$, and acceptance set $X = \{start\_rescue\}$.

\[
T_T(s, a_1) = \text{pass} \rightarrow start\_recovery \rightarrow \text{fail} \rightarrow \text{Stop}
\]
\[
T_F(s, X) = \text{fail} \rightarrow start\_recovery \rightarrow \text{pass} \rightarrow \text{Stop}
\]

They can both be used to kill $ppoParIntERSystem1$ and $ppoParIntERSystem2$.

Appendix B.2. Mutations by $ppoParSeq$

The parallel composition in the definition of $ERSystem$ is changed to a sequential composition by the concurrency mutation operator $ppoParSeq$. The result of the mutation is shown in Figure B.22. In the two produced mutants, the first process of the resulting sequential composition has a non-terminating looping behavior: both $ERU$ and $InitiateRescueOrFault$ are non-terminating. This makes the second process in the sequential composition unreachable. As an strategy to kill the mutants, test cases can be based on traces that exercise events exclusively available in the unreachable process.

The behavior of the mutant $parSeqERSystem1$, for example, is restricted to that defined by $InitiateRescueOrFault$, at the left of the sequential composition, in parallel with $Recovery$. Such behavior is identical to that of $ERSystem$ while it holds that $allocated < total\_erus$ in the $ERU$ process. To expose this, we need a trace to reach a state in $ERSystem$ where $allocated = total\_erus$ and check for a forbidden
process \( ERU \equiv \text{begin} \)
  state \( \text{Control} \equiv [\text{allocated}, \text{total}_\text{erus} : \mathbb{N}] \)
  InitControl \( \equiv [\text{Control} \mid \text{allocated}' = 0 \land \text{total}_\text{erus}' = 5] \)
  AllocateState \( \equiv [\Delta \text{Control} \mid \text{allocated}' = \text{allocated} + 1] \)
  Allocate \( \equiv \text{allocate}_\text{idle}_\text{eru} \rightarrow \text{AllocateState} \land \text{Choose} \)
  ServiceState \( \equiv [\Delta \text{Control} \mid \text{allocated}' = \text{allocated} - 1] \)
  Service \( \equiv \text{service}_\text{rescue} \rightarrow \text{ServiceState} \land \text{Choose} \)
  Choose \( \equiv \begin{cases} \text{Allocate} & (\text{allocated} = \text{total}_\text{erus}) \rightarrow \text{Service} \\ \text{Allocate} & (\text{allocated} > 0 \land \text{allocated} < \text{total}_\text{erus}) \rightarrow \text{Service} \end{cases} \)
  \text{fi} \)

• InitControl; Choose
end

process InitiateRescueOrFault \( \equiv \text{begin} \)
  CallCentreStart \( \equiv \text{start}_\text{rescue} \rightarrow \text{FindIdleEru} \)
  FindIdleEru \( \equiv \text{find}_\text{idle}_\text{erus} \rightarrow (\text{IdleEru} \square (\text{wait} \rightarrow \text{FindIdleEru})) \)
  IdleEru \( \equiv \text{allocate}_\text{idle}_\text{eru} \rightarrow \text{send}_\text{rescue}_\text{info}_\text{to}_\text{eru} \rightarrow \text{IR1} \)
  IR1 \( \equiv \text{process}_\text{message} \rightarrow \text{FAReceiveMessage} \land \text{fault}_\text{activation} \rightarrow \text{IR2} \)
  FAReceiveMessage \( \equiv \text{receive}_\text{message} \rightarrow \text{ServiceRescue} \)
  ServiceRescue \( \equiv \text{service}_\text{rescue} \rightarrow \text{CallCentreStart} \)
  IR2 \( \equiv \text{IR2Out} \land \text{error}_\text{detection} \rightarrow \text{FASStartRecovery} \)
  IR2Out \( \equiv \text{drop}_\text{message} \rightarrow \text{target}_\text{not}_\text{attended} \rightarrow \text{CallCentreStart} \)
  FASStartRecovery \( \equiv \text{start}_\text{recovery} \rightarrow \text{end}_\text{recovery} \rightarrow \text{ServiceRescue} \)

• CallCentreStart
end

channelset ERUSignals \( \equiv \{\text{allocate}_\text{idle}_\text{eru}, \text{service}_\text{rescue}\} \)
channelset RecoverySignals \( \equiv \{\text{start}_\text{recovery}, \text{end}_\text{recovery}\} \)
process ERSystem \( \equiv \)
  (InitiateRescueOrFault \[ ERUSignals \] ERU) \[ RecoverySignals \] Recovery

Figure B.20: ERS Specification

process \( \text{ppoParIntERSystem1} \equiv \)
  (InitiateRescueOrFault \[ ERUSignals \] ERU) \[ RecoverySignals \] Recovery

process \( \text{ppoParIntERSystem2} \equiv \)
  (InitiateRescueOrFault \[ ERUSignals \] ERU) \[ RecoverySignals \] Recovery

Figure B.21: ppoSeqInt ERSystem mutants

43
process \( \text{parSeqERSystem1} \equiv \)
\((\text{InitiateRescueOrFault}; \text{ERU}) [\text{RecoverySignals}] \text{Recovery} \)

process \( \text{parSeqERSystem2} \equiv \)
\((\text{InitiateRescueOrFault} [\text{ERUSignals}] \text{ERU}); \text{Recovery} \)

Figure B.22: Mutations by \( \text{ppoParSeq} \)

continuation \( a_2 = \text{allocate}_\text{idle}_\text{eru} \) and acceptance set \( X_2 = \{\text{wait}\} \). Below, we have a trace \( s_1 \) of both \( \text{parSeqERSystem1} \) and \( \text{ERSystem} \).

\[
s_1 = (\text{start}_\text{rescue}, \text{find}_\text{idle}_\text{eru},
\text{allocate}_\text{idle}_\text{eru}, \text{send}_\text{rescue}_\text{info}_\text{to}_\text{eru}, \text{fault}_\text{activation}, \text{drop}_\text{message}, \text{target}_\text{not}_\text{attended})
\]

In \( \text{ERSystem} \), in the execution of this trace, the state of the process \( \text{ERU} \) is changed by increasing in the value of \( \text{allocated} \) by 1. Such trace can be repeatedly observed in the execution of \( \text{ERSystem} \) up to five times, until \( \text{allocated} = \text{total}_\text{erus} \), when no more units are available and the minimal acceptance set is a single \( \text{wait} \) event. The mutant \( \text{parSeqERSysstem1} \), on the other hand, is able to perform the forbidden continuation \( \text{allocate}_\text{idle}_\text{eru} \) and, therefore, can be killed by the test cases below.

\[
T_T(s_1^5 \equiv (\text{start}_\text{rescue}, \text{find}_\text{idle}_\text{eru}), \text{allocate}_\text{idle}_\text{eru})
\]
\[
T_F(s_1^5 \equiv (\text{start}_\text{rescue}, \text{find}_\text{idle}_\text{eru}), \{\text{wait}\})
\]

We use \( s_1^5 \) to represent the trace containing five consecutive copies of \( s_1 \). We omit the explicit definition of the above tests due to their size.

The mutation inflicted in \( \text{parSeqERSystem2} \) removes the \( \text{Recovery} \) process from the parallel execution, as it becomes the second part of the sequential composition. So, the events in this process are absent in the mutant. The following trace

\[
s_2 = (\text{start}_\text{rescue}, \text{find}_\text{idle}_\text{eru}, \text{allocate}_\text{idle}_\text{eru}, \text{send}_\text{rescue}_\text{info}_\text{to}_\text{eru},
\text{fault}_\text{activation}, \text{error}_\text{detection}, \text{start}_\text{recovery})
\]

is both a trace of \( \text{parSeqERSystem2} \) and \( \text{ERSystem} \). In \( \text{ERSystem} \), however, the next events are from \( \text{Recovery} \), which is not reachable in the mutant \( \text{parSeqERSystem2} \). So, the following tests can kill the mutant.

\[
T_T(s_2, \text{end}_\text{recovery}) =
\]
\[
in\rightarrow \text{start}_\text{rescue} \rightarrow \text{pass} \rightarrow \text{find}_\text{idle}_\text{eru}
\rightarrow \text{pass} \rightarrow \text{allocate}_\text{idle}_\text{eru} \rightarrow \text{pass} \rightarrow \text{send}_\text{rescue}_\text{info}_\text{to}_\text{eru}
\rightarrow \text{pass} \rightarrow \text{fault}_\text{activation} \rightarrow \text{pass} \rightarrow \text{error}_\text{detection}
\rightarrow \text{pass} \rightarrow \text{start}_\text{recovery} \rightarrow \text{pass} \rightarrow \text{end}_\text{recovery}
\rightarrow \text{fail} \rightarrow \text{Stop}
\]
\[ T_F(s_2, \{ \text{log\_fault} \}) = \]
\[
\text{inc} \rightarrow \text{start\_rescue} \rightarrow \text{fail} \rightarrow \text{find\_idle\_eru} \\
\rightarrow \text{fail} \rightarrow \text{allocate\_idle\_eru} \rightarrow \text{fail} \rightarrow \text{send\_rescue\_info\_to\_eru} \\
\rightarrow \text{fail} \rightarrow \text{fault\_activation} \rightarrow \text{fail} \rightarrow \text{error\_detection} \\
\rightarrow \text{fail} \rightarrow \text{start\_recovery} \rightarrow \text{fail} \rightarrow \text{log\_fault} \\
\rightarrow \text{pass} \rightarrow \text{Stop}
\]

Considering the trace \( s_2 \), we can use the forbidden continuaton \textit{end\_recovery} and the minimal acceptance set \{ \text{log\_fault} \} to obtain the tests shown above.

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