

Towards Compositional Synthesis of Evolving Systems

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ABSTRACT

Synthesis of system configurations from a given set of features is an important and very challenging problem. This paper makes a step towards this goal by describing an efficient technique for synthesizing pipeline configurations of feature-based systems. We identify and formalize a design pattern that is commonly used in feature-based development. We show that this pattern enables *compositional* synthesis of feature arrangements. In particular, the pattern allows us to add or remove features from an existing system without having to reconfigure the system from scratch. We describe an implementation of our technique and evaluate its applicability and effectiveness using a set of telecommunication features from AT&T, arranged within the DFC architecture.

Categories and Subject Descriptors

D.2.1 [Software Engineering]: Requirements/Specifications

General Terms

Design, Verification

Keywords

Feature-Based Development, Synthesis, Behavioural Design Patterns, Pipelines, I/O Automata.

1. INTRODUCTION

Feature-based development has long been used as a way to provide separation of concerns, to facilitate maintenance and reuse, and to support software customization based on end-user needs [33, 23, 17, 1, 24]. Individual features typically capture specific units of functionality with direct relationships to the requirements that inspired the software system in the first place [14]. By closely mirroring requirements, features make it easier to reconfigure or expand a system as its underlying requirements change over time.

To meet the desirable properties expected from a feature-based system, the interactions among its features need to be constrained and orchestrated. This is often done by putting features in a suitable arrangement, typically a linear one such as a stack or a pipeline, that inhibits undesirable interactions.

Existing research on feature interaction analysis, e.g., [32, 20, 18, 16, 30, 23, 13, 7], largely concentrates on reasoning about and resolving undesirable interactions between a set of features *whose arrangement is given a priori*. Yet a complementary problem, of how to automatically synthesize an arrangement when one is not given, has not been studied much. The problem is important – it currently takes substantial expertise and effort to find an arrangement of features that does not result in undesirable interactions.

Unfortunately, a naive attempt at automatically arranging features is infeasible: there is an exponential number of alternative arrangements to consider when searching for a desirable one. Hence, we need compositional techniques that can reduce the problem of finding a desirable arrangement into smaller subproblems. This need becomes even more pressing in systems that evolve over time, where features are periodically added, removed, or revised. Without compositional techniques for synthesizing evolving systems, new arrangements of features may have to be created from scratch after each change.

Our goal is to provide compositional techniques for synthesizing software systems from an *evolving, arbitrarily large* set of (*different*) features. To achieve this goal, we draw inspiration from the literature on component-based software. A general way to enable compositional reasoning about systems with an arbitrary number of components is by exploiting behavioural similarities between components. For example, [12, 11] show that system-wide verification tasks can be decomposed if components exhibit identical or virtually identical behaviours. The motivation for the work is verification of low-level operating system protocols, e.g., mutual exclusion where several identical copies of a process attempt to enter a critical section. More recent work, e.g., [2], explores similar ideas to bring compositional reasoning to software systems in which components have diverse behaviours. There, the required degree of similarity between components is achieved by having components implement a *design pattern*.

In this paper, we aim to study how the design patterns used in feature-based development can enable compositional synthesis of feature arrangements. We ground our work on *pipelines* – popular architectures for building feature-based systems [4, 20, 18, 23] which allow one to define the overall behaviour of a system in terms of a simple composition of the behaviours of the individual features [35].

A common objective in designing feature pipelines is to minimize the visibility of each feature to the rest. This is to ensure that individual features can operate without relying on those appearing before or after them in the pipeline [35]. To realize this objective, features are usually designed such that they engage in defining the overall behaviour of the system only when their function is needed. More precisely, features alter the flow of signals in the pipeline only

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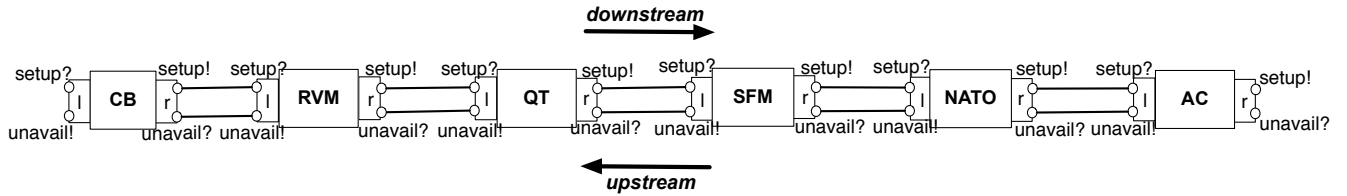


Figure 1: A simplified linear DFC scenario.

when they are providing their service; otherwise, they let the signals pass through without side-effects. The ability of a feature to remain unobservable to other features when it is not providing its service is called *transparency*.

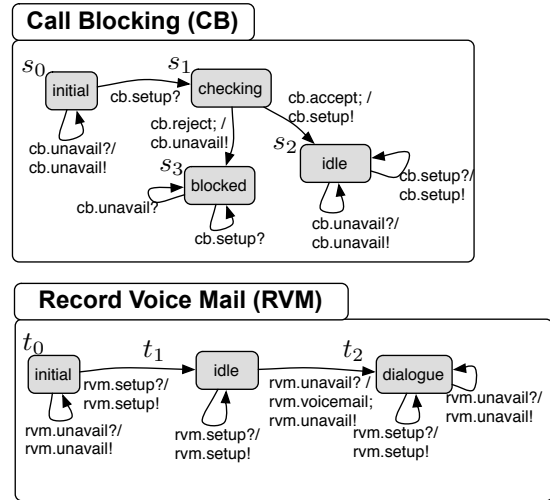
In this paper, we argue that transparency is sufficient to make pipeline synthesis compositional, requiring the analysis of just pairs of features to determine their relative order in the overall pipeline. In particular, we make the following contributions:

1. We formalize the transparency pattern of behaviour and show that for features implementing this pattern, *global* constraints can be inferred on the order of the features through *pairwise* analysis of the features.
2. We describe a *sound* and *complete* compositional algorithm for synthesizing pipeline arrangements. Given a set of features and a set of safety properties describing undesirable interactions, our algorithm computes an arrangement of the features that is safe for the given properties. Specifically, the algorithm uses the safety properties to compute a set of pairwise ordering constraints between the features. Due to the transparent behaviour of the features, any global ordering that violates a pairwise ordering constraint can be deemed unsafe and pruned from the search space of the solution, leaving a relatively small number of global orderings to be generated and verified by the algorithm. Our algorithm is *change-aware* in the sense that after adding or modifying a feature, we need to update only the pairwise ordering constraints related to that particular feature and reuse the remaining constraints from the previous system.
3. We report on a prototype implementation of our synthesis algorithm, applying it to a set of AT&T telecom features to find a safe arrangement for them in the Distributed Feature Composition (DFC) architecture [20]. Our algorithm could automatically and efficiently compute the same arrangement as was manually constructed by a domain expert.

The rest of the paper is organized as follows. In Section 2, we motivate our work using an example from the telecom domain. After fixing the notation and reviewing basic notions of refinement and model checking in Section 3, we formalize features as I/O automata and define a notion of binding for describing pipelines in Section 4. Section 5 is the main contribution of the paper. It formalizes the transparency pattern that guarantees that synthesis can be done compositionally. We describe our synthesis algorithm in Section 6 and its implementation in Section 7. In Section 8, we evaluate our technique on a set of AT&T telecom features. We review related work and compare it with our approach in Section 9 and conclude the paper with a summary of contributions and an outline of future research directions in Section 10.

2. MOTIVATION

We motivate our work by analyzing a simplified instance of a telecom scenario (see Figure 1). Features in this scenario are arranged in a pipeline and include Call Blocking (CB), Record Voice



To distinguish between input, output, and internal actions, we append to each action e the symbol “?” if e is an input action, the symbol “!” if e is an output action, and the symbol “;” if e is an internal action. Further, to disambiguate between the actions of different state machines, we prefix every action with the name of the state machine it belongs to.

Figure 2: Call Blocking (CB) and Record Voice Mail (RVM).

Mail (RVM), Quiet Time (QT), Sequential Find Me (SFM), No Answer Time Out (NATO), and Answer Confirm (AC).

Pipeline features communicate by passing signals to their immediate neighbours. Signals that travel end-to-end pass through all features, allowing each feature to perceive and modify the overall function of the pipeline. For example, Figure 1 shows the flow of the signals *setup* and *unavail*. There are many other signal types, but we show only the most relevant ones here.

The communication between the features in a pipeline is either buffered or unbuffered (synchronous). The former facilitates reliable communication but complicates reasoning: it is known that verification of a distributed system with unbounded buffers is undecidable [5]. Instead, we assume that features communicate through synchronous message passing, which makes for more tractable reasoning but imposes restrictions on the design of features: they should be responsive to *all* potential input at all time, i.e., they should be *input-enabled*. This requirement is captured in a number of standard formalisms for describing concurrent systems, e.g., I/O automata [25]. For example, all the features in Figure 1 are enabled for *setup* and *unavail*.

To refer to the directions within a pipeline, we use the terms *upstream* (right to left) and *downstream* (left to right). In our example, the *setup* signal travels downstream, and the *unavail* signal travels upstream. For features F and F' in a pipeline, we write $F < F'$ to indicate that F is upstream (“to the left of”) of F' . For example, in Figure 1, $CB < NATO$.

Figure 2 shows the state machines for CB and RVM in the pipeline of Figure 1. The purpose of CB is to block calling requests coming

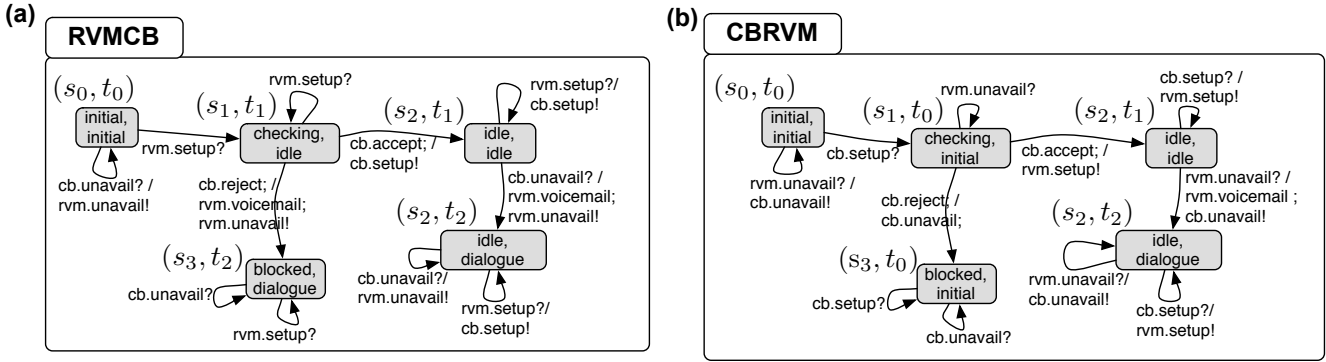


Figure 4: The compositions of the features in Figure 2 with respect to the orderings in Figure 3.

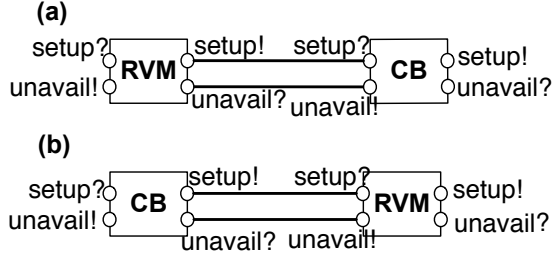


Figure 3: Possible orderings of the features in Figure 2.

from addresses on a blocked list. CB becomes active by receiving a setup signal containing initialization data such as the directory numbers of the caller and callee. Using this data and its internal logic, CB decides whether the caller should be blocked. If so, it moves to the blocked state and tears down the call; otherwise, it moves to the idle state and effectively becomes invisible. The purpose of RVM is to record a voicemail message when the callee is not available. Like CB, RVM becomes active by receiving a setup signal. It then remains in its idle state until it receives an unavail signal, indicating that the callee is unavailable or is unable to receive the call. Upon receipt of this signal, RVM records a voicemail message through interactions with its media resource, as represented by the internal action `voicemail`, and then enters the dialogue state.

Feature Interaction. The behaviour of the composition of the features in a pipeline depends on the ordering of the features, and the goal of our work is to synthesize an ordering which will guarantee absence of undesirable compositions. For example, suppose we are trying to avoid the composition: “RVM should not record a message if CB blocks the caller” [37], formalized as the following negative trace¹:

$$NS_1 = \text{cb.reject}; \text{rvm.voicemail};$$

CB and RVM can be put in a pipeline one of the two ways, shown in Figure 3. The ordering in Figure 3(a) yields the composition in Figure 4(a), and the one in Figure 3(b) – the composition in Figure 4(b). The composition in Figure 4(a) results in an undesirable interaction: the path from (s_0, t_0) to (s_3, t_2) generates the trace NS_1 , i.e., “`rvm.voicemail;`” comes after “`cb.reject;`”. The composition in Figure 4(b), on the other hand, does not exhibit NS_1 , implying that CB should come before RVM in a pipeline.

Synthesis Challenge. In general, finding a suitable ordering cannot

¹The trace “`rvm.voicemail;` `cb.reject;`” could have been considered instead of NS_1 as well.

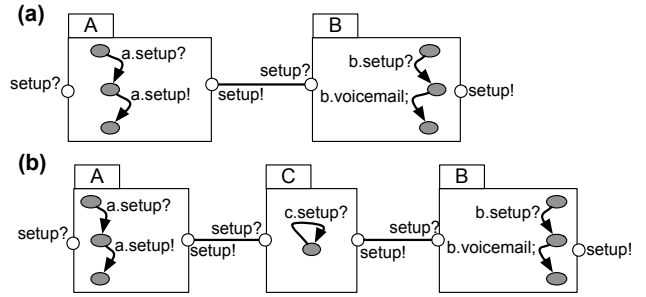


Figure 5: Local ordering vs. global ordering.

be done compositionally when the features in a pipeline have unconstrained designs. For example, consider sample features A and B in Figure 5(a) and the property “A voicemail message should not be recorded”², i.e., action “`b.voicemail;`” must not be produced by the composition of A and B . This property does not hold over either a pipeline in which $A < B$, or the one in which $B < A$. In the former case, A sends `setup` to B , and B generates “`b.voicemail;`”, and in the latter case, B receives `setup` from the environment and generates “`b.voicemail;`”. So, it may seem that the given correctness property does not hold on a pipeline containing A and B . However, consider the new feature C in Figure 5(b) which blocks the action `setup`. The pipeline $A < C < B$ in Figure 5(b) satisfies the given correctness property, i.e., the composition of these features, when arranged in the above order, does not generate “`b.voicemail;`”. This example shows that, in general, we may not be able to infer a global ordering over the pipeline by analyzing subsets of components. Even though the given correctness property only concerns B , our analysis needs to consider *all* the components in the pipeline. Hence, given n unrestricted components, we need to check exponentially many ($n! \approx O(2^{n \log n})$) pipeline arrangements to find one which satisfies the properties of interest. This is intractable for all but the most trivial pipelines.

Transparency Pattern. To be able to lift an ordering over a subset of pipeline features to the entire pipeline, we rely on a pattern of behaviour called *transparency*. Each feature implementing this pattern can exhibit an execution along which it is unobservable (transparent). When executing transparently, a feature sends any signal received from its left to its right, and any signal received from its right to its left, possibly with some finite delay. Features implementing the transparency pattern can still perform their specific functionality via other executions, or via unobservable behaviours.

²This property is used only for illustration.

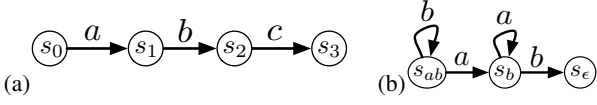


Figure 6: Examples of LTSs.

For example, in Figure 2, CB’s transparent execution is from s_0 to s_2 , and RVM’s – from t_0 to t_2 . CB behaves transparently if the call request comes from a non-blocked address. In this case, the system proceeds as if CB were never present; otherwise, CB provides its service by blocking the incoming call, i.e., by taking the path from s_0 to s_3 . As for RVM, the feature is always transparent and its function, recording a voicemail message, is carried out through its internal behaviour which is invisible to other features.

For pipeline features implementing the transparency pattern, we prove the following (Section 5): if a pipeline consisting of just two features F and F' where $F < F'$ violates a safety property φ , a pipeline with an arbitrary number of components in which $F < F'$ violates φ as well. This enables a compositional algorithm for synthesizing pipeline orderings (Section 6).

3. PRELIMINARIES

In this section, we fix the notation and provide background on composition semantics, refinement, and model checking.

Labelled Transition Systems (LTS). An LTS is a tuple $M = (S, s_0, E, R)$ where S is a set of states, $s_0 \in S$ is an initial state, E is a set of actions, and $R \subseteq S \times E \times S$ is a set of transitions. We write a transition $(s, e, s') \in R$ as $s \xrightarrow{e} s'$.

Two example LTSs are shown in Figure 6. A *trace* of an LTS M is a *finite* sequence σ of actions that M can perform starting at its initial state. For example, ϵ , a , ab , and abc are traces of the LTS in Figure 6(a). The set of all traces of M is called the language of M , denoted $\mathcal{L}(M)$. We say $\sigma = e_0e_1 \dots e_n$ is a trace over Σ if $e_i \in \Sigma$ for every $0 \leq i \leq n$. We denote by Σ^* the set of all finite traces over Σ .

Let M be an LTS, and $E' \subseteq E$. We define $M@E'$ to be the result of restricting the set of actions of M to E' , i.e., replacing actions in $E \setminus E'$ with the unobservable action τ and reducing E to E' . For an LTS M with τ -labelled transitions, we consider $\mathcal{L}(M)$ to be the set of traces of M with the occurrences of τ removed. This is a standard way for hiding unobservable computations of LTSs [22].

Composition. The composition of two LTSs that run asynchronously and communicate through synchronous message passing is formalized as *parallel composition* [28]. The parallel composition operator \parallel combines the behaviours of two LTSs by synchronizing their shared actions and interleaving their non-shared ones. Unless stated otherwise, it is assumed that actions with identical names are shared, and the rest are non-shared.

DEFINITION 1 (PARALLEL COMPOSITION [28]). Let $M_1 = (S_1, s_0, E_1, R_1)$ and $M_2 = (S_2, t_0, E_2, R_2)$ be LTSs. The parallel composition of M_1 and M_2 , denoted $M_1 \parallel M_2$, is defined as an LTS $(S_1 \times S_2, (s_0, t_0), E_1 \cup E_2, R)$, where R is the smallest relation satisfying the following:

$$R = \{((s, t), e, (s', t)) \mid (s, e, s') \in R_1 \wedge e \notin E_2\} \cup \{((s, t), e, (s, t')) \mid (t, e, t') \in R_2 \wedge e \notin E_1\} \cup \{((s, t), e, (s', t')) \mid (s, e, s') \in R_1 \wedge (t, e, t') \in R_2\}$$

Refinement. Refinement formalizes the relation between two LTSs at different levels of abstraction. Refinement is usually defined as

a variant of *simulation*. In this paper, we use the notion of *weak simulation* (also known as *observational simulation*) to check the existence of a refinement relation between two LTSs [28]. This notion can be used for relating LTSs with different sets of actions by replacing their non-shared actions with τ . For states s and s' of an LTS M , we write $s \xrightarrow{\tau} s'$ to denote $s(\xrightarrow{\tau})^* s'$. For $e \neq \tau$, we write $s \xrightarrow{e} s'$ to denote $s(\xrightarrow{\tau})(\xrightarrow{e})(\xrightarrow{\tau})s'$.

DEFINITION 2 (SIMULATION [28]). Let M_1 and M_2 be LTSs, where $E_1 = E_2 = E$. A relation $\preceq \subseteq S_1 \times S_2$ is a weak simulation, or simulation for short, where $s \preceq t$ iff

$$\forall s' \in S_1. \forall e \in E \cup \{\tau\}. s \xrightarrow{e} s' \Rightarrow \exists t' \in S_2. t \xrightarrow{e} t' \wedge s' \preceq t'$$

We say M_2 simulates M_1 , written $M_1 \preceq M_2$, iff $s_0 \preceq t_0$

THEOREM 1. [28] Let M_1 and M_2 be LTSs where $M_1 \preceq M_2$. Then, $\mathcal{L}(M_1) \subseteq \mathcal{L}(M_2)$.

Based on the above theorem, simulation is a sufficient condition for trace containment. Recall that $\mathcal{L}(M_1)$ and $\mathcal{L}(M_2)$ capture only the *observable* behaviours of M_1 and M_2 . Thus, Theorem 1 states that if $M_1 \preceq M_2$, then M_2 can generate every observable trace of M_1 , but not necessarily traces with τ -steps.

Model Checking. We express correctness properties as finite negative traces over the set of actions of a system. Negative traces characterize the behaviours that a system must not exhibit (*safety* properties). For example, the property NS_1 described in Section 2 is a safety property for a telecom system with features CB and RVM. To satisfy this property, the system must not allow “rvm.voicemail;” to occur after “cb.reject;”, i.e., the trace “cb.reject; rvm.voicemail;” is a negative trace.

Let $M = (S, s_0, E, R)$ be an LTS, and let $\sigma = e_1e_2 \dots e_n$ be a trace over E' where $E' \subseteq E$. We say the M satisfies a negative trace σ if $\sigma_{stat} \notin \mathcal{L}(M@E')$, where $\sigma_{stat} = (E' \setminus e_1)^* e_1 (E' \setminus e_2)^* e_2 \dots (E' \setminus e_n)^* e_n$. That is, the system that needs to exclude NS_1 should not allow the trace $b^* a a^* b$, where $a =$ “cb.reject;” and $b =$ “rvm.voicemail;”, either. This can be determined by translating σ to a safety LTS M_σ and computing the parallel composition of M and M_σ (e.g., see [26]). Formally, let σ be a trace over E' . A *safety LTS* M_σ is a tuple (S, s_σ, R, E') where

$$S = \{s_{\sigma'} \mid \sigma' \text{ is a (possibly empty) suffix of } \sigma\}$$

$$R = \{(s_{\sigma'}, e, s_{\sigma''}) \mid \sigma' = e.\sigma'' \wedge \sigma' \text{ is a suffix of } \sigma\} \cup \{(s_{\sigma'}, e', s_{\sigma'}) \mid \sigma' = e.\sigma'' \wedge e' \in E' \wedge e \neq e' \wedge \sigma' \text{ is a suffix of } \sigma\}$$

For example, the LTS in Figure 6(b) can be interpreted as the safety LTS for the negative trace NS_1 in Section 2 by letting $a =$ “cb.reject;” and $b =$ “rvm.voicemail;”. Note that state s_ϵ , which corresponds to the empty suffix ϵ , is without outgoing transitions in every safety LTS. Reachability of this state determines whether M can generate σ . That is, $\sigma_{stat} \notin \mathcal{L}(M@E')$ iff state s_ϵ is not reachable in $M_\sigma \parallel M$. Thus, model checking an LTS M against a negative trace σ can be done by composing M with M_σ and checking reachability of s_ϵ .

4. I/O AUTOMATA AND PIPELINES

We describe features as I/O automata [25]. This formalism is chosen because (1) I/O automata allow distinguishing between the input, internal, and output actions of features – this distinction between different types of actions is crucial for properly describing the communications between features [25]; and (2) I/O automata are input-enabled by design. Input-enabledness makes it easier to detect and avoid deadlocks [25, 38] and further, provides a way to terminate features that are stuck in error loops and hence are wasting resources [38].

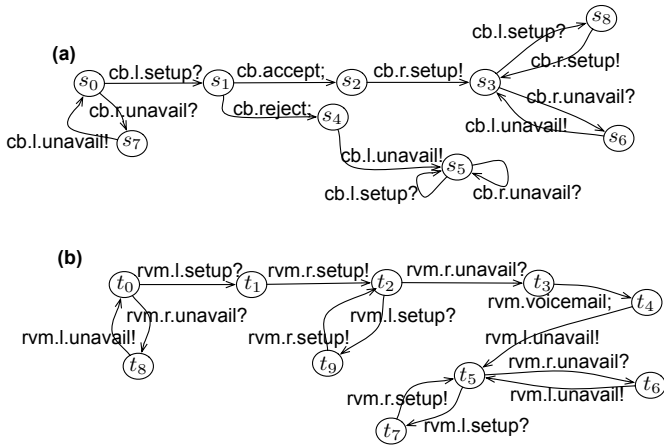


Figure 7: I/O automata for the state machines in Figure 2.

DEFINITION 3 (I/O AUTOMATA [25]). An I/O automaton is a tuple $A = (S, s_0, E, R)$, where S is a finite set of states; $s_0 \in S$ is an initial state; E is a set of actions partitioned into input actions (E^i), output actions (E^o), and internal actions (E^h); and $R \subseteq S \times E \times S$ is a set of transitions.

Input actions are those that a feature receives from its environment. Internal actions represent events scoped inside a feature and invisible outside of it. Examples of such events include internal timers and communication with media devices. Output actions represent a feature’s response to its input and internal actions.

An I/O automaton can be viewed as an LTS if the distinction between input, output and internal actions is ignored. Given an I/O automaton $A = (S, s_0, E = E^i \cup E^o \cup E^h, R)$, we write $LTS(A)$ to denote the LTS (S, s_0, E, R) . Similar to LTSs, we write $A@E'$ to denote A with its set of actions reduced from E to E' , and write $\mathcal{L}(A)$ to denote the set of traces of A . Figures 7(a) and (b) show the I/O automata for the state machines in Figures 2(a) and (b), respectively. The labels of the input and output actions of these I/O automata have infixes “r” (right) and “l” (left); these indicate the directions in which these actions are communicated (see Definition 4).

We say a state s is *enabled* for an action e if s has an outgoing transition labelled e . A state s is *quiescent* if s is not enabled for any output or internal actions. Intuitively, an automaton in a quiescent state is strictly waiting for an input from its environment. An I/O automaton A is *input-enabled* if the following conditions hold:

1. A returns promptly to some quiescent state after leaving one. We assume the execution time of transitions labelled with output and internal actions to be negligible. Thus, prompt return to a quiescent state means that output and internal actions never block the execution, and further, no cycle of transitions labelled with only internal and output actions exists.
2. Quiescent states of A are enabled for all input actions. For example, states s_0 , s_3 , and s_5 in Figure 7(a) are quiescent and are enabled for all input actions of CB, i.e., “cb.l.setup?” and “cb.r.unavail?”.

As shown in Figure 1, each feature has one port on its left and one on its right side, and actions can be sent or received from either of these two ports. To be able to refer to the direction of communication in a pipeline, we augment I/O automata with action mappings which specify the port from which an action is sent or received.

DEFINITION 4 (FEATURES). A feature F is a tuple (A_F, f) where A_F is an I/O automaton, and $f : E^i \cup E^o \rightarrow \{r, l\}$ is a function that maps every input and output action of F to either the right, r, or the left, l, port of F . We write “ $F.r.e$ ” (or, respectively, “ $F.l.e$ ”) to say that action e is mapped to port “r” (or, respectively, “l”).

Note that f does not map the internal actions of a feature because these actions are invisible outside the feature.

In Figure 1, the smaller boxes attached to the features denote the ports. Actions are visualized as small circles on the appropriate ports. For example, CB has an (output) action “cb.r.setup!” mapped to its right port, and RVM has an (input) action “rvm.l.setup?” mapped to its left port.

To formally specify how two consecutive features in a pipeline communicate, we define a notion of *binding* for connecting the right port of one feature to the left port of another.

DEFINITION 5 (PIPELINE BINDINGS). Let F_1 and F_2 be consecutive features in a pipeline; let $R = \{e \in E_1 \mid f_1(e) = r\}$; and let $L = \{e \in E_2 \mid f_2(e) = l\}$. A (pipeline) binding $B \subseteq R \times L$ between F_1 and F_2 is a one-to-one correspondence relation between L and R that relates input actions only to output actions, and output actions only to input actions; i.e.,

$$(e_1, e_2) \in B \implies ((e_1 \in E_1^o \wedge e_2 \in E_2^i) \vee (e_1 \in E_1^i \wedge e_2 \in E_2^o))$$

For a binding B , we say an action is *shared* if it occurs in some tuple of B , and *non-shared* otherwise.

The links between the features in Figure 1 can be expressed as bindings. For example, the CB–RVM link in the figure is characterized by the following binding:

$$B = \{(\text{cb.r.setup!}, \text{rvm.l.setup?}), (\text{cb.r.unavail?}, \text{rvm.l.unavail!})\}$$

which indicates that the output action “cb.r.setup!” (of CB) synchronizes with the input action “rvm.l.setup?” (of RVM), and the input action “cb.r.unavail?” (of CB) synchronizes with the output action “rvm.l.unavail!” (of RVM).

In our working example, bindings are meaningful only if they relate actions with identical signal names. For example, had we considered an additional upstream-traveling signal, unknown in Figure 1, it would have been incorrect to, say, relate actions “cb.r.unknown?” and “rvm.l.unavail!”. Thus, in this paper we assume that features use a unified set of signals and all bindings are based on signal name equivalences. On the other hand, we recognize that there may be domains where this assumption does not hold: features may refer to a shared signal by different names, or refer to non-shared signals by the same name. Through making mappings between actions explicit, all such bindings can be captured by Definition 5 directly.

To obtain the overall behaviour of a set of communicating features, we compose them with respect to the bindings established between them. To this end, we define a parallel composition of I/O automata, whereby features synchronize their shared actions and interleave their non-shared ones.

DEFINITION 6 (COMPOSITION OF PIPELINE FEATURES). Let F_1 and F_2 be consecutive features in a pipeline linked by a binding B . The parallel composition of F_1 and F_2 with respect to B , denoted $F_1 ||_B F_2$, is a feature (A, f) where

- $A = (S_1 \times S_2, (s_0, t_0), E = E^i \cup E^o \cup E^h, R)$ with E^i , E^o , E^h , and R defined as followed:

$$\begin{aligned}
E^i &= (E_1^i \cup E_2^i) \setminus \{e \mid e \text{ is a shared input action}\} \\
E^o &= (E_1^o \cup E_2^o) \setminus \{e \mid e \text{ is a shared output action}\} \\
E^h &= (E_1^h \cup E_2^h) \cup B \\
R &= \{(s, t), e, (s', t') \mid (s, e, s') \in R_1 \wedge e \text{ is a non-shared action}\} \cup \\
&\quad \{(s, t), e, (s', t') \mid (t, e, t') \in R_2 \wedge e \text{ is a non-shared action}\} \cup \\
&\quad \{(s, t), (e, e'), (s', t') \mid (s, e, s') \in R_1 \wedge (t, e', t') \in R_2 \wedge (e, e') \in B\} \\
\bullet f &= (f_1 \cup f_2) \setminus \{e \mid e \text{ is a shared action}\}
\end{aligned}$$

The above is the same as the standard definition of parallel composition for I/O automata [25], except that we use bindings to explicitly specify the shared actions prior to composition. Since bindings are one-to-one, it easily follows that the \parallel_B operator is associative. Thus, the global composition of the features in a pipeline can be formulated as a series of binary compositions.

5. FORMALIZING TRANSPARENCY

Intuitively, if a feature F implements the transparency pattern (motivated in Section 2), then there is *some* environment that coerces F to exhibit its transparent behaviour. For example, CB (in Figure 2) exhibits its transparent execution, i.e., from s_0 to s_2 , when data from the environment indicates that the callee has not blocked the caller. Since pipeline features act independently [20, 35], each feature can be coerced into its transparent execution independently of other features.

In this section, we formalize the above intuition and prove (in Theorem 2) that if all features implement the transparency pattern, the following holds:

“If a pipeline with two features (F followed by F') violates a safety property φ , a pipeline with an arbitrary number of features in which $F < F'$ violates φ as well.”

We exploit this result in Section 6 to provide a compositional algorithm for ordering features in a pipeline.

The formalization of the transparency pattern G is shown in Figure 8. It is expressed as an I/O automaton with generic input actions $G.l.\langle x \rangle?$ and $G.r.\langle y \rangle?$, and generic output actions $G.l.\langle y \rangle!$ and $G.r.\langle x \rangle!$. State S_0 is quiescent, and states S_1 and S_2 are transient. A feature implementing this pattern can exhibit some execution along which it forwards any signal it receives from its left port onto its right port, and vice versa. On this execution, a feature can delay the transmission of actions for a *finite* amount of time to perform its internal behaviours, but is not allowed to add or omit any actions, or to change the order of actions being transmitted. If the environmental data is such that a feature has to provide its service in response, the feature chooses a non-transparent execution or simply fulfills its functionality through internal actions on its transparent execution.

The cycle between states S_0 and S_1 in Figure 8 (hereafter, the *downstream cycle*) handles signals that travel downstream, and the cycle between S_0 and S_2 (hereafter, the *upstream cycle*) handles signals traveling upstream. To adapt the generic transparency pattern to a specific pipeline problem, we need a copy of the downstream cycle for every signal traveling downstream, and a copy of the upstream cycle for every signal traveling upstream. For example, Figure 9 shows the adaptation, P , of the pattern to the pipeline in Figure 1. Since this pipeline has one downstream traveling signal, *setup*, and one upstream traveling signal, *unavail*, P has one copy of the downstream and one copy of the upstream cycle. Had we considered further signals, we would have had more copies of the corresponding cycles in this adaptation.

We characterize the implementation relation between a feature and its adaptation by weak simulation (see Definition 2), which allows us to relate features with different sets of actions. Having such flexibility is key: although the features in a pipeline share the same

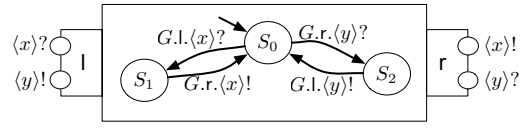


Figure 8: G : Generic transparency pattern.

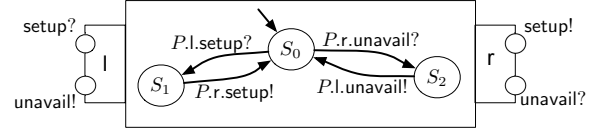


Figure 9: P : Adaptation of the generic transparency pattern to the pipeline in Figure 1.

input and output actions with the pattern adaptation, each feature has its own set of internal actions. For example, consider features CB and RVM in Figure 7. CB’s internal actions are “cb.reject;” and “cb.accept;”, whereas RVM’s is “rvm.voicemail;”. Such internal actions are not used in P in Figure 9.

To establish a simulation relation between a feature and its pattern adaptation, we need to hide the feature’s internal actions. For example, after replacing actions “cb.reject;” and “cb.accept;” of CB and “rvm.voicemail;” of RVM with τ , both CB and RVM simulate P . The simulation relation for CB is $\{(s_0, S_0), (s_1, S_1), (s_2, S_1), (s_3, S_0), (s_6, S_2), (s_7, S_2), (s_8, S_1)\}$, and for RVM is $\{(t_0, S_0), (t_1, S_1), (t_2, S_0), (t_3, S_2), (t_4, S_2), (t_5, S_0), (t_6, S_2), (t_7, S_1), (t_8, S_2), (t_9, S_1)\}$.

Before giving the main result of this section, Theorem 2, we state two lemmas used in the proof of the theorem. For the remainder of this section, let P be the adaptation of the generic transparency pattern, G , for a particular pipeline.

LEMMA 1. *Let F be a feature, and let B_1 bind $F.r$ to $P.l$. If F violates a desired safety property, so does $F \parallel_{B_1} P$. Similarly, let B_2 bind $P.r$ to $F.l$. If F violates a desired safety property, so does $P \parallel_{B_2} F$.*

The proof of this lemma follows from the fact that the set of traces of an arbitrary pipeline feature F is preserved in the composition of F with P , i.e., P does not affect traces of the composition.

The following lemma states that if the features in a pipeline implement the transparency pattern, so does the entire pipeline. That is, the features cannot prohibit one another from exhibiting their transparent behaviour.

LEMMA 2. *Let F_1, \dots, F_n be consecutive features in a pipeline, where B_i binds $F_i.r$ to $F_{i+1}.l$. If every F_i ($1 \leq i \leq n$) implements (i.e., weak simulates) P , so does the composition*

$$F_1 \parallel_{B_1} F_2 \parallel_{B_2} \dots \parallel_{B_{n-1}} F_n.$$

Finally, we present the main theorem of this section:

THEOREM 2. *Let F, F', F_1, \dots, F_n be pipeline features, and let F, F' and every F_i ($1 \leq i \leq n$) implement P . If the pipeline in Figure 10(a) does not satisfy a desired safety property, neither does the pipeline in Figure 10(b).*

Proof (sketch). Let X_1 be the pipeline segment from F_1 to F_{i-1} , X_2 be the segment from F_i to F_j , and X_3 be the segment from F_{j+1} to F_n in Figure 10(b). Suppose X is the pipeline obtained

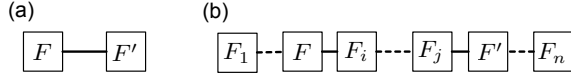


Figure 10: An illustration for Theorem 2.

by replacing each X_1 , X_2 and X_3 in Figure 10(b) with P , i.e., X consists of F , F' and three instances of P . By Lemma 2, if X is not safe, neither is the pipeline in Figure 10(b). By Lemma 1 and Theorem 1 in Section 3, if the pipeline in Figure 10(a) is not safe, neither is X .

We use Theorem 2 to propose an efficient pipeline ordering algorithm, described in Section 6.

6. COMPOSITIONAL SYNTHESIS

In this section, we describe the algorithm for computing ordering of features in a pipeline, to ensure that they do not admit any of the undesirable interactions. The algorithm, ORDERPIPELINE, is shown in Figure 11. The main engine of this algorithm is the function FINDPAIRWISECONSTRAINTS, shown in Figure 12, which computes a set \mathcal{C} of ordering constraints between feature pairs. These constraints are inferred by model checking the two possible compositions of each feature pair against the safety properties defined over that pair. For example, let $F_1 = \text{CB}$ and $F_2 = \text{RVM}$, and let $\text{negTr} = \text{NS}_1$ (see Section 2). With these inputs, FINDPAIRWISECONSTRAINTS yields $\text{CB} < \text{RVM}$ because the property NS_1 holds in the composition where CB comes before RVM (line 5 in Figure 12), but not in the other composition (line 7). The resulting constraint $\text{CB} < \text{RVM}$ is added to \mathcal{C} (line 11) which is returned on line 16. By Theorem 2, a pipeline ordering that does not respect pairwise ordering constraints is unsafe, and thus inadmissible. This provides us with an effective strategy for pruning the search space for solutions.

Given a pair of features, FINDPAIRWISECONSTRAINTS can infer an ordering over the pair, if exactly one of their two possible compositions violates the given properties. Otherwise, if neither composition violates the properties, the features in question can be put in any order, and hence no constraint is derived (line 15). If both compositions violate the properties, FINDPAIRWISECONSTRAINTS returns error (line 9). In this case, the given features need to be revised before they can be put together in a pipeline; hence, ORDERPIPELINE terminates unsuccessfully (line 3).

If FINDPAIRWISECONSTRAINTS does not return error, ORDERPIPELINE enters a repeat-until loop (lines 4–8). Every iteration of this loop starts by finding a permutation of the n features comprising the pipeline that satisfies the set of constraints computed by FINDPAIRWISECONSTRAINTS. Such a permutation, called T , satisfies a set \mathcal{C} of constraints if for every constraint $F_k < F_l$ in \mathcal{C} , we have $T[k] < T[l]$, i.e., feature F_k is positioned to the left of feature F_l in the pipeline. For example, let $F_1 = \text{CB}$, $F_2 = \text{QT}$, and $F_3 = \text{RVM}$. The permutation T satisfying constraints $\{\text{CB} < \text{RVM}, \text{RVM} < \text{QT}\}$ is $[1, 3, 2]$. Afterwards, a global composition of the features is built with respect to the computed permutation T . If this composition satisfies all the given properties, T is returned as a solution. Otherwise, the loop continues until a solution is found, or all permutations that satisfy \mathcal{C} are exhausted. In the latter case, ORDERPIPELINE returns error.

Notice that merely satisfying \mathcal{C} does not make a given permutation T a solution to the pipeline ordering problem. For example, consider features A and B in Figure 13(a)³. The composition of A

³This example is similar to that given in Section 2, but the details

Algorithm. ORDERPIPELINE

Input: - Features F_1, \dots, F_n with action sets E_1, \dots, E_n , respectively.
- A set $\text{negTr} \subseteq (\bigcup_{1 \leq k \leq n} E_k)^*$ of negative traces.

Output: A permutation, T , of 1 to n giving an order on F_1, \dots, F_n .

```

1:  $\mathcal{C} := \text{FINDPAIRWISECONSTRAINTS}(F_1, \dots, F_n, \text{negTr})$ 
2: if ( $\mathcal{C} = \text{error}$ ):
3:   return error
4: repeat
5:    $T := \text{Next permutation of } 1, 2, \dots, n \text{ satisfying } \mathcal{C}$ 
6:   Let  $B_i$  bind  $F_{T[i]}.r$  to  $F_{T[i+1]}.l$  for  $1 \leq i < n$ 
   //  $B_i$  connects the feature at position  $i$  to the one at position  $i + 1$ 
7:    $\text{safe} := \text{MODELCHECK}(F_{T[1]} ||_{B_1} \dots ||_{B_{n-1}} F_{T[n]}, \text{negTr})$ 
8: until safe
9: return T

```

Figure 11: Algorithm for pipeline ordering.

Algorithm. FINDPAIRWISECONSTRAINTS

Input: Features F_1, \dots, F_n and negative trace negTr .

Output: A set \mathcal{C} or pairwise ordering constraints.

```

1:  $\mathcal{C} := \emptyset$ 
2: for  $1 \leq k < l \leq n$ : // choose a pair  $F_k, F_l$ 
3:    $\text{negTr}' := \text{negTr} \cap (E_k \cup E_l)^*$  // restrict  $\text{negTr}$  to  $F_k$  and  $F_l$ 
4:    $B_1 := \text{Binding}(F_k.r, F_l.l)$  // put  $F_k$  before  $F_l$ 
5:    $\text{safe}_1 := \text{MODELCHECK}(F_k ||_{B_1} F_l, \text{negTr}')$ 
6:    $B_2 := \text{Binding}(F_l.r, F_k.l)$  // put  $F_k$  after  $F_l$ 
7:    $\text{safe}_2 := \text{MODELCHECK}(F_k ||_{B_2} F_l, \text{negTr}')$ 
8:   if ( $\neg \text{safe}_1 \wedge \neg \text{safe}_2$ ):
9:     return error
10:  if ( $\text{safe}_1 \wedge \neg \text{safe}_2$ ):
11:    add  $F_k < F_l$  to  $\mathcal{C}$ 
12:  else if ( $\neg \text{safe}_1 \wedge \text{safe}_2$ ):
13:    add  $F_l < F_k$  to  $\mathcal{C}$ 
14:  else: // i.e.,  $\text{safe}_1 \wedge \text{safe}_2$ 
15:    do nothing // inconclusive result; no constraint on  $F_k$  w.r.t.  $F_l$ 
16: return C

```

Figure 12: Algorithm for finding pairwise ordering constraints.

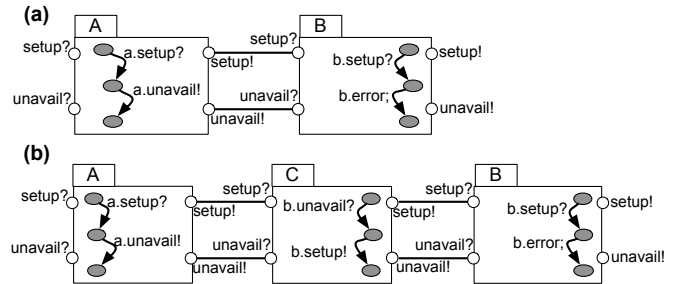


Figure 13: Local ordering vs. global ordering.

and B in the figure is safe for the trace “b.error;”, i.e., “the error action is unreachable”. However, once feature C is inserted between A and B in Figure 13(b), the resulting pipeline is no longer safe for this property: Theorem 2 only guarantees safety violations to lift from a pairwise to the global setting. However, safety properties

are not identical.

that are *satisfied* over a pair of features are not necessarily lifted⁴. Therefore, we need to check all safety properties over the global composition induced by a candidate ordering. Further, although in practice most safety property traces are expressed over pairs of features, we can envision traces that refer to several and potentially to all features in the system. Checking such properties requires the construction of a global composition.

Our pipeline ordering algorithm is *sound* because we construct a global composition and verify it against all the given properties. The algorithm is *complete* because by Theorem 2, it never prunes an ordering that is a possible solution to the pipeline ordering problem. Finally, the algorithm is *change-aware*, allowing for the reuse of synthesis results across changes to pipelines. Specifically, after adding or modifying a feature F , all we need to do is to (re)compute the pairwise constraints between F and the rest of the features in the pipeline. In other words, constraints not involving F remain valid and can be carried over from the previous system.

The scalability and effectiveness of our approach ultimately depend on how well we can narrow down the search for potentially admissible pipeline permutations, and whether verifying compositions (lines 5 and 7 in Figure 12, and line 7 in Figure 11) is feasible. In Section 8, we apply our approach to an industrial telecom example. There, we demonstrate that substantial pruning of the search space can be achieved by utilizing the pairwise constraints inferred from the known undesirable interactions in the domain. The features used in our evaluation were not very large, and therefore, we could verify their compositions in a conventional way. But, for larger systems, we can improve the scalability of ORDERPIPELINE algorithm using existing automated compositional techniques for checking safety properties (e.g., [9]).

7. IMPLEMENTATION

We have developed a prototype implementation of the pipeline ordering algorithm described in Section 6. We discuss inputs to the algorithm as well as the relevant technical details below.

Inputs. Our algorithm in Section 6 receives a set of features expressed as I/O automata and a set of negative traces capturing undesirable interactions between these features. In order to use standard verification tools, in our case, the LTS Analyzer (LTSA) tool [26], our tool translates the input features to LTSs and the negative traces – to safety LTSs (see Section 3).

Parallel composition. Our technique requires us to compute compositions of pipeline features (lines 5 and 7 of FINDPAIRWISECONSTRAINTS in Figure 12 and line 7 of ORDERPIPELINE in Figure 11), for which we need to implement the parallel composition operator $||_B$ (Definition 6) – one is not readily available in LTSA. This is achieved as follows: first, we do an action relabelling to ensure that shared actions, with respect to a given binding B , have identical labels in the features to be composed. We then apply LTSA’s parallel composition operator (Definition 1) to compose the features.

Model checking. Since we translate negative traces to safety LTSs, model checking (lines 5 and 7 of FINDPAIRWISECONSTRAINTS and line 7 of ORDERPIPELINE) can be done directly using LTSA. Note that our technique involves model checking not only pairwise but also the global composition (line 7 of ORDERPIPELINE). Our tool currently uses LTSA directly for this latter check, which has

⁴The features in Figure 13 can be completed to implement the transparency pattern (the completions not shown here due to space limitations) and yet exhibit the same problem.

not presented a challenge so far because the number and the size of features we have been working with so far have been relatively small (see Section 8). However, this check may become an issue when analyzing larger systems, and in the future we intend to use an enhanced version of LTSA [9] that enables compositional model checking for safety properties. This approach applies to our work directly, since the negative traces we use are safety properties.

Ordering permutations. To generate ordering permutations that satisfy a given set of constraints (line 5 of ORDERPIPELINE), we use a backtracking constraint solver, Choco [21]. All constraints used in our approach are binary, and for those, the state-of-the-art look-ahead techniques for solving CSP problems are very efficient.

8. EVALUATION

In this section, we provide initial evidence for the usefulness of our approach through a case study from the telecom domain. Our study involves six features from AT&T deployed in the DFC architecture [20].

When conducting the study, we had a number of goals. The first goal was to check that the features present in the case study simulate our formalization of the transparency pattern in Figure 9 (**G1**). The other two goals were to investigate whether our technique can sufficiently narrow down the search for a safe pipeline ordering, which includes the ability to identify enough negative scenarios of interaction (**G2**), and to evaluate the performance of our technique on a realistic example (**G3**). We begin this section with a description of the domain of our study, and discuss the experience with the above goals in Section 8.2.

8.1 Domain Description

In DFC, a simple telecom usage is implemented by a linear pipeline such as the one shown in Figure 1. The original DFC pipeline has several additional signals, e.g., *avail* and *unknown*, which we omitted from Figure 1 for simplicity. The pipeline in the figure includes six features, namely, CB and RVM (see Section 2), as well as QT, SFM, NATO, and AC. A high-level description of the four new features, taken from [37], is as follows:

Quiet Time (QT) enables the subscriber to avoid an incoming call by activating a dialog with the caller, saying that the subscriber wishes not to be disturbed. If the caller indicates that the call is urgent, this feature allows the call to go through. Otherwise, it signals failure (*unavail*) upstream.

Sequential Find Me (SFM) attempts to find the callee at a sequence of locations. If the first location does not succeed, then while all the other locations are being tried, the feature plays an announcement, letting the caller know that the call is still active.

No Answer Time Out (NATO) signals failure (*unavail*) upstream if an incoming call is not answered after a certain amount of time.

Answer Confirm (AC) uses a media resource to elicit confirmation that the call has been answered by a person rather than by a machine. If the test is not passed, it signals *unavail* upstream, even though the call was actually answered.

The DFC architecture supports dynamic architectural reconfiguration. This means that features and bindings can be created, destroyed, or reassigned at runtime. In fact, the pipeline in Figure 1 is a static snapshot of a dynamic structure. For example, in the figure, each new location tried by SFM results in a new setup signal

Feature	CB	RVM	QT	SFM	NATO	AC
# of states	9	10	12	22	7	10
# of transitions	13	13	19	31	16	21

Table 1: Sizes of the resulting translations.

sent downstream, and creation of new instances of NATO and AC. We do not consider such advanced capabilities here. Specifically, we abstract away feature behaviours involving runtime reconfiguration. Hence, a pipeline ordering synthesized by our technique is over a static snapshot of a (potentially) dynamic DFC pipeline. In this sense, the real value of our technique with respect to DFC is as an exploration tool through which analysts can consider different snapshots of the same pipeline and ensure that the synthesized orderings for these snapshots are consistent with one another.

The features in our case study are specified in Boxtalk [38] – a domain-specific language for specifying telecom features. Each Boxtalk specification is a state machine with a set of states and a set of transitions which can be triggered by actions. Boxtalk also provides constructs for manipulating data and media, but we do not consider these constructs in this work. Boxtalk is similar to I/O automata in that the models described in it are input-enabled; the language also distinguishes between input, output, and internal actions of features [38]. Hence, the control behaviours of Boxtalk specifications can be conveniently captured using our I/O automata-based formalism (Definition 4).

In this case study, all of the features except NATO and CB have additional ports through which they communicate with media resources that record speech, play announcements, detect touch-tones, etc. We have abstracted away from these ports, replacing their signals with internal actions such as “rvm.voicemail;”. This abstraction is safe because the interaction of each feature with its media resource is independent and logically contained within the feature, thus not affecting feature composition.

8.2 Experience

We manually translated the six Boxtalk features into I/O automata. The sizes of the translated models are shown in Table 1, whereas the original Boxtalk specifications and the resulting I/O automata are available in [29].

Our analysis indicates that all these features implement our formalization of the transparency pattern. We already exemplified the simulation relation for CB and RVM in Section 5. For the remaining features, see [29]. The realization of the transparency pattern satisfies goal **G1** and enables the application of our pipeline ordering algorithm.

G2. The set of nine negative scenarios used in the study is shown in Table 2. These scenarios came from [37] and from experience of the domain expert – the last author of this paper. Table 2 shows the constraints inferred by our technique for each individual scenario, and the composition of these constraints was enough to reduce the set of possible global solutions to the pipeline ordering problem to a single arrangement.

While we had no problem in this domain where the nature of interactions between feature pairs was well studied and well understood, our technique may be less effective in other domains. The degree to which it narrows down the search is influenced by factors such as the size and the number of features in the domain, the amount of domain expertise available, and the existence of formal design guidelines for feature development, and all of these may vary widely.

To extend the applicability of our approach to domains where an adequate set of negative scenarios is hard to obtain, the approach

Negative Scenario	Constraint
RVM should not record a voicemail message from a caller blocked by CB.	CB < RVM
QT cannot stop a caller from putting a voicemail message.	RVM < QT
AC cannot ask for confirmation from a callee if he/she has enabled QT and the call is not urgent.	QT < AC
RVM should not record a voicemail message if NATO reports that the callee is available.	RVM < NATO
QT should not ask a blocked caller whether his/her call is urgent.	CB < QT
SFM should not attempt to find the callee if QT is enabled and the call is not urgent.	QT < SFM
SFM should not wait for the callee if NATO times out	SFM < NATO
RVM should not record a message if SFM has not yet tried all the callee’s locations.	RVM < SFM
NATO cannot report the availability of the callee if AC has not yet received a confirmation from the callee.	NATO < AC

Table 2: Negative scenarios and the resulting constraints.

can be combined with simulation and monitoring tools which assist users in identifying additional undesirable scenarios. The idea is that analysts often have certain heuristics for detecting “suspicious” behaviour, even though they may not have pinned down the exact undesirable interactions. For example, it might be dangerous for certain pairs of features to be active in the same usage scenario. The ability of a tool to report pairs of features that can be active simultaneously may help analysts to identify additional safety properties and thus reduce the number of feature orderings.

Different monitoring tools can be used in conjunction with our approach, but the one that readily integrates with our formalism is LTSA’s simulation module. This module can be used to monitor the parallel composition of a set of features and report traces leading to suspicious behaviours. These traces can then be studied by analysts as potential candidates for negative scenarios. Since our approach requires traces only over pairs of features to infer ordering constraints, users can concentrate on pairwise compositions, for which traces are typically small and intuitive enough for manual inspection.

G3. We measured the time and memory performance of the different steps in our technique, applied to the features in our study. The reported times are for a PC with a 2.2GHz Pentium Core Duo CPU and 2GB of memory; our implementation used version 1.2 of Choco and version 2.3 of LTSA.

FINDPAIRWISECONSTRAINTS: Executing lines 5 and 7 of this algorithm (Figure 12) involves building pairwise compositions of LTSs and model checking them. Since I/O automata can be seen as LTSs, the sizes of our LTS translations are those shown in Table 1. The number of states of the pairwise compositions ranged between 60 to 259, and the number of transitions between 210 to 785. The running times for generating the compositions were negligible, i.e., under 1s.

To model check the compositions, we expressed safety properties as (safety) LTSs, which, for the properties in Table 2, ranged between 3 to 5 states, and 5 to 8 transitions. For example, Figure 6 can be interpreted as a safety LTS for the property NS_1 described in Section 2 by letting $a = \text{“cb.reject;”}$ and $b = \text{“rvm.voicemail”}$. The running times of individual model checking tasks were negligible.

For the six features in the study and the properties in Table 2, the total execution time of FINDPAIRWISECONSTRAINTS was 6.47s and the maximum required memory was 10M. The result of running the algorithm is the set of ordering constraints in the second column of Table 2.

ORDERPIPELINE: Line 5 of this algorithm (Figure 11) invokes a

constraint solver Choco to compute a permutation satisfying the pairwise ordering constraints. The running time and memory usage of this step were negligible due to the nature of our CSP problem (see Section 7), and resulted in a single permutation that satisfied all of the pairwise constraints in Table 2.

Line 7 of the ORDERPIPELINE algorithm requires computing a global composition of the features. Since there is only one permutation satisfying the constraints in Table 2, only one global composition needed to be built and verified. The number of states and transitions in this global composition are 1.5×10^6 and 22×10^6 , respectively⁵. The time and memory needed for generating this composition are 71.4s and 913M, respectively. The total model checking time, i.e., the sum of model checking times for individual properties in Table 2, was 16min, and the maximum memory requirement was 1G.

Overall, we were able to compute the same order that the domain expert produced by hand completely automatically, in about a quarter of an hour. However, as the above numbers show, the size of global composition grows quickly, and compositional techniques for dealing with this space explosion are needed. But, as we discussed in Section 7, compositional tools applicable to our problem already exist, and will be incorporated into our approach in the near future.

9. RELATED WORK

The ideas and techniques presented in this paper are related to a variety of research areas such as concurrent systems [25, 26], web service composition [15], behavioural synthesis [36], software architectures [35, 26], etc. A complete survey of all these threads is not intended here, and instead, we focus on comparing our work with the most relevant research thrusts.

Feature interaction is a well studied problem in feature-based software development, and many approaches addressing this problem have been proposed, e.g., [20, 3, 18, 30, 16, 23]. Some of the earlier work required extensive manual intervention. For example, [3] proposed a logic-based approach for detecting undesirable interactions by manually instrumenting potential interactions with exception clauses and employing a theorem prover for finding inconsistencies. [30] developed a scheme whereby users manually specify the join points at which new features can be inserted into a base system. Feature interactions are explored by weaving the features and model checking the result.

Recent approaches offer better automation: [18] resolves undesirable interactions using predefined priorities prescribing which feature should be favoured should a conflict arise. [23] proposes a compositional method for verifying features that are composed sequentially through known interface states. [16] provides an automated unification operator for combining features (described in a functional language) with respect to given unifiers. These approaches assume that the relationships between features (i.e., priorities in [18], interfaces in [23], and unifiers in [16]) are developed *a priori*. Our work deals with a complimentary problem of how to *synthesize* these relationships.

Several approaches propose the use of architectural styles, such as layered [6, 32] or pipeline architectures [20, 4], as a way to prevent undesirable interactions. The arrangement of features within these architectures is typically done manually. Our work offers a solution to automate this task for the pipeline architectural style.

Our work also relates to [10] which focuses on verifying port-based systems (with buffered links between features). The work

⁵We have observed that global compositions for other permutations are of roughly the same size.

builds on domain-specific knowledge about the DFC architecture, such as regularity of feature properties and symmetry of communication port behaviours, to enable compositional verification of DFC usage pipelines. However, [10] does not address the synthesis of these pipelines, and also does not exploit the transparent behaviours of DFC features for reasoning.

Compositional analysis extends the applicability of verification methods by reducing reasoning about a large system to reasoning about its individual components. For example, assume-guarantee reasoning [31] enables verification of individual components in conjunction with assumptions about their environment, and allows lifting of the results to the entire system. Existing work on this topic is not directly applicable to synthesis of feature-based systems because one needs to know about the bindings between features in order to specify the environmental assumptions. However, our synthesis algorithms could directly benefit from *automated* assume-guarantee techniques for safety properties, e.g., [9]. Specifically, our feature ordering algorithm in Section 6 involves model checking pairwise and global compositions induced by specific bindings. These model checking tasks can be done more efficiently using the technique of [9].

Design for verification promotes the use of domain-specific patterns and guidelines to facilitate efficient automated verification [34, 27, 2, 8]. For example, [2] provides a concurrency controller pattern for making verification of concurrent Java programs more scalable, and [34] studies the use of structural design guidelines for efficient verification of UML models. To the best of our knowledge, the use of patterns for compositional reasoning about feature-based systems has not been investigated previously.

10. CONCLUSION

In this paper, we presented a sound and complete compositional approach for synthesizing feature arrangements. The formal groundwork for our technique is a pattern of behaviour called transparency. We proved that this pattern enables inferring global constraints on feature arrangements through pairwise analysis of the features. We reported on a prototype implementation and preliminary evaluation of our work for synthesizing orderings of AT&T telecom features. Our experience shows that our approach can efficiently compute the ordering of features in a DFC pipeline, obtaining the same results as computed by hand by a domain expert.

In our case study, the desired properties were described as negative traces (safety). Our algorithm can also readily work with positive traces. In fact, a corollary of Theorem 2 is that the transparency pattern lifts existence of positive traces from a pairwise to the global setting. We leave extending our technique to (finite) liveness, i.e., dealing with *universal* positive behaviours, to future work.

Further, the properties in our case study did not contradict one another. However, one could envision cases where some of these properties are mutually inconsistent. Our feature ordering algorithm detects such inconsistencies as circular, or over-constrained, orderings. Alternatively, users may want to establish consistency before applying our algorithm, e.g., using Alloy [19].

While this paper focused on pipeline arrangements, our technique can be used for synthesis of more complex arrangements as well. In particular, we can synthesize graph arrangements consisting of linear pipeline segments by first synthesizing the segments and then combining them to construct the overall system.

Our current approach assumes that each feature implements a distinct requirement. Yet, it is possible for individual features, par-

ticularly in legacy systems, to implement multiple functions, each invoked depending on external parameters or user preferences. Our approach may create circular dependencies between such features. We leave the methodology of breaking these cycles and dealing with parameterized feature arrangements for future work.

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