CS:5810 Formal Methods in Software Engineering

A Mode-aware Contract Language for Reactive Systems

Overview

Introduction to contract-based compositional reasoning and its advantages

Introduction of new specification language aimed at facilitating

- modular development and
- compositional reasoning

Discussion of

- implementation in Kind 2 model checker
- examples of contract-based specifications

Compositional Reasoning in Kind 2

Based on Assume/Guarantee Paradigm

Every component $C[\mathbf{x}, \mathbf{y}]$ with inputs $\mathbf{x}$ and outputs $\mathbf{y}$ has a *contract*:

- a set $\mathcal{A}[\mathbf{x}]$ of *assumptions* on C's environment
- a set $\mathcal{G}[\mathbf{x}, \mathbf{y}]$ *guarantees* on how C must behave, provided assumptions $\mathcal{A}[\mathbf{x}]$ hold

C *respects* its contract $\langle \mathcal{A},\ \mathcal{G} \rangle$ if all of its executions satisfy[1]

$$\Box\,\mathcal{A} \;\Rightarrow\; \Box\,\mathcal{G}$$

[1] Formula $\Box\,\varphi$ is true iff φ is true at all times

Assume/Guarantee Reasoning (simplified form)

Def. A component $C_1[\mathbf{x}_1, \mathbf{y}_1]$ *uses* a component $C_2[\mathbf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input **a** and reads the corresponding output in **b**

Assume/Guarantee Reasoning (simplified form)

Def. A component $C_1[\mathbf{x}_1, \mathbf{y}_1]$ *uses* a component $C_2[\mathbf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input $\mathbf{a}$ and reads the corresponding output in $\mathbf{b}$

Let $(\mathcal{A}[\mathbf{x}_i], \mathcal{G}[\mathbf{x}_i, \mathbf{y}_i])$ be the contract of C_i for $i = 1, 2$

Assume/Guarantee Reasoning (simplified form)

Def. A component $C_1[\mathsf{x}_1, \mathbf{y}_1]$ *uses* a component $C_2[\mathsf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input $\mathbf{a}$ and reads the corresponding output in $\mathbf{b}$

Let $(\mathcal{A}[\mathsf{x}_i], \mathcal{G}[\mathsf{x}_i, \mathbf{y}_i])$ be the contract of C_i for $i = 1, 2$

Def. C_1 uses C_2 *safely* if C_1's executions satisfy $\Box\, \mathcal{A}_2[\mathbf{a}]$

Assume/Guarantee Reasoning (simplified form)

Def. A component $C_1[\mathbf{x}_1, \mathbf{y}_1]$ *uses* a component $C_2[\mathbf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input $\mathbf{a}$ and reads the corresponding output in $\mathbf{b}$

Let $(\mathcal{A}[\mathbf{x}_i], \mathcal{G}[\mathbf{x}_i, \mathbf{y}_i])$ be the contract of C_i for $i = 1, 2$

Def. C_1 uses C_2 *safely* if C_1's executions satisfy $\Box\, \mathcal{A}_2[\mathbf{a}]$

Note If C_1 uses C_2 safely and C_2 respects its contract, one can assume $\Box\, \mathcal{G}_2[\mathbf{a}, \mathbf{b}]$ to prove that C_1 respects its contract

Assume/Guarantee Reasoning (simplified form)

Def. A component $C_1[\mathbf{x}_1, \mathbf{y}_1]$ *uses* a component $C_2[\mathbf{x}_2, \mathbf{y}_2]$ if it feeds C_2 some input $\mathbf{a}$ and reads the corresponding output in $\mathbf{b}$

Let $(\mathcal{A}[\mathbf{x}_i], \mathcal{G}[\mathbf{x}_i, \mathbf{y}_i])$ be the contract of C_i for $i = 1, 2$

Def. C_1 uses C_2 *safely* if C_1's executions satisfy $\Box\, \mathcal{A}_2[\mathbf{a}]$

Note If C_1 uses C_2 safely and C_2 respects its contract, one can assume $\Box\, \mathcal{G}_2[\mathbf{a}, \mathbf{b}]$ to prove that C_1 respects its contract

Effectively, this means that C_2 can be abstracted by its contract

Modularity in Lustre

Components defined as *nodes* parametrized by inputs

Can have several outputs

Can be understood as macros

```
node MinMaxSoFar ( X : real ) returns ( Min, Max : real );
let
  Min = X -> if (X < pre Min) then X else pre Min ;
  Max = X -> if (X > pre Max) then X else pre Max ;
tel

node MinMaxAverageSoFar ( X: real ) returns ( Y: real ) ;
var Min, Max: real ;
let
  Min, Max = MinMax(X) ;
  Y = (Min + Max)/2.0 ;
tel
```

CocoSpec Contract Language

An extension of Lustre with contracts

Objectives:

- compatibility with the widespread assume / guarantee paradigm
- ease the process of writing and reading formal specifications
- facilitate automatic verification of specs
- improve feedback to user after analysis
- partition information for specification-driven test generation

Contract-based specification

Contracts over components

- describe their behavior under some assumptions
- correspond to requirements from the specification documents

Contract Example

stopwatch($\texttt{toggle}$, $\texttt{reset}$) $\rightarrow$ $\texttt{count}$

Assumptions:

- legit input $\neg(\texttt{reset} \wedge \texttt{toggle})$

Guarantees:

- output range $\texttt{count} \geq 0$
- resetting $\texttt{reset}$ implies $\texttt{count}$ is 0
- running $\neg\texttt{reset} \wedge \texttt{on}$ implies $\texttt{count}$ increases by one
- stopped $\neg\texttt{reset} \wedge \neg\texttt{on}$ implies $\texttt{count}$ does not change

Contract Example

```
node stopwatch(toggle, reset: bool) returns (c: int);
(*@contract
  var on: bool = toggle ->
    (pre on and not toggle) or (not pre on and toggle) ;

  assume not (reset and toggle) ;
  guarantee c >= 0 ;

  guarantee reset => c = 0 ;
  guarantee (not reset and on) => c = (1 -> pre c + 1) ;
  guarantee (not reset and not on) => c = (0 -> pre c) ;
*)
let ... tel
```

Modes

Often, specifications are contextual (mode-based):

when/if this is the case, do that

Assume/Guarantee contracts do not adequately capture this sort of specifications

Modes are simply encoded as conditional guarantees

Modes: Example

stopwatch(`toggle`, `reset`) $\rightarrow$ `count`

Assumption:

- legit input $\neg($`reset` $\wedge$ `toggle`$)$

Guarantee:

- output range `count` ≥ 0

Modes:	require	ensure
• resetting	`reset`	`count` is 0
• running	$\neg$`reset` $\wedge$ `on`	`count` increases by one
• stopped	$\neg$`reset` $\wedge$ $\neg$`on`	`count` does not change

Modes in CocoSpec

CocoSpec represents modes explicitly

A mode consists of a *require* (`req`) and an ensure (`ens`) clause

- expresses a transient behavior
- corresponds to a guarantee `req` $\Rightarrow$ `ens`

$\Rightarrow$ separation between global behavior (guarantees)
and transient behavior (modes)

Modes in Contract

A set of modes M can be added to a contract

Its semantics is an assume / guarantee pair $\langle \mathcal{A}, \mathcal{G} \rangle$ with

$$\mathcal{A} \equiv \bigvee_{m \in M} \mathtt{req}_m$$

$$\mathcal{G} \equiv \bigwedge_{m \in M} (\mathtt{req}_m \Rightarrow \mathtt{ens}_m)$$

Modes: Example

stopwatch(toggle, reset) $\to$ count

```
var on: bool = toggle -> (pre on and not toggle) or (not pre on and
 toggle) ;
```

Assumption:

- legit input $\neg$(reset $\wedge$ toggle)

Guarantee:

- output range count ≥ 0

Modes:	require	ensure
• resetting	reset	count $= 0$
• running	$\neg$reset $\wedge$ on	count increases by one
• stopped	$\neg$reset $\wedge$ $\neg$on	count does not change

Motivation

Detect shortcomings in the specification:

- do the modes cover all situations the assumptions allow?
- enables specification-checking before model-checking

Motivation

Detect shortcomings in the specification:

- do the modes cover all situations the assumptions allow?
- enables specification-checking before model-checking

Produce better feedback for counterexamples:

- indicate which modes are active at each step
- provide a mode-based abstraction of the concrete values
- abstraction is in terms of the user-specified behaviors

CocoSpec Contracts

A CocoSpec contract is

- a set of assumptions,
- a set of guarantees, and
- a set of modes

Can contain *internal* variables

It can use *specification* nodes

Can be *inlined* in a node or *stand-alone*

Stand-alone contracts can be imported and instantiated

Stand-alone Contract with Modes

```
contract stopwatch_spec(tgl, rst: bool) returns (c: int) ;
let
  var on: bool = tgl -> (pre on and not tgl) or (not pre on and tgl) ;

  assume not (rst and tgl) ;
  guarantee c >= 0 ;

  mode resetting (
    require rst ; ensure c = 0 ; ) ;
  mode running (
    require not rst and on ; ensure c = (1 -> pre c + 1) ; ) ;
  mode stopped (
    require not rst and not on ; ensure c = (0 -> pre c) ; ) ;
tel

node stopwatch(toggle, reset: bool) returns (count: bool) ;
(*@contract import stopwatch_spec(toggle, reset) returns (count) ; *)
let ... tel
```

Additional Features

In contracts, one can

- refer to modes in formulas (with `::<mode_name>`)
- call contract-free nodes

```
node count(in: bool) returns (count: int) ;
let
  count = (if in then 1 else 0) + (0 -> pre count) ;
tel

contract stopwatch_spec(tgl, rst: bool) returns (c: int) ;
let
  ...
  mode running (...) ;
  mode stopped (...) ;

  guarantee not (::running and ::stopped) ;
  guarantee ( count(::resetting) > 0 ) => ( c < count(true) ) ;
tel
```

Contracts as an Abstraction Mechanism

A component's contract is usually simpler than the component's definition

A contract is a declarative over-approximation of the component

Contracts enable modular and compositional analyses in alternative to a monolithic one

In compositional analyses we abstract away the complexity of a component by its contract

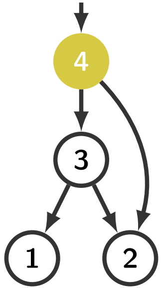
Monolithic Analysis

Monolithic:

- analyze the top level
- considering the whole system

But

- complete system might be too complex
- changing subcomponents voids old results
- correctness of subcomponents is not addressed

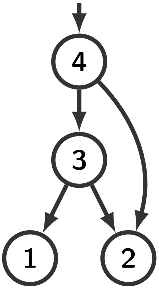


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

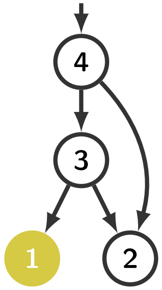


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

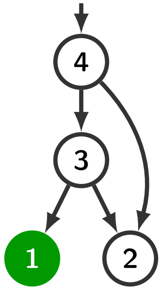


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

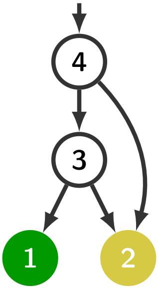


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

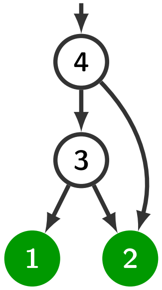


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

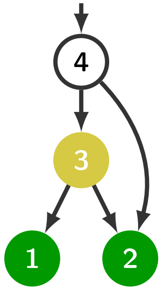


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

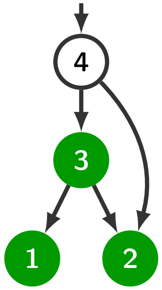


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

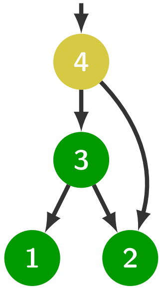


Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But



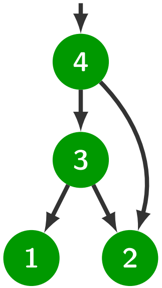
Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

- changing subcomponents voids old results



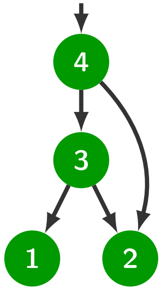
Modular Analysis

Modular:

- analyze all components bottom-up
- reusing results from subcomponents

But

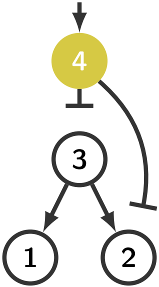
- changing subcomponents voids old results
- complexity can explode as we go up



Compositional Analysis

Compositional:

- analyze the top level
- abstracting subnodes by their contracts
- complexity of the system analyzed is reduced
- changing subcomponents preserves old results
  (as long as new versions are correct)

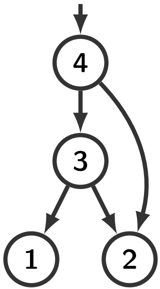


But

- counterexamples might be spurious
- correctness of subcomponents is assumed

Compositional and Modular

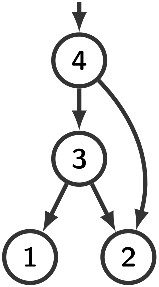
Compositional and modular:



Compositional and Modular

Compositional and modular:

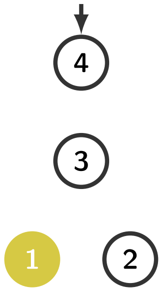
- no abstraction for the leaf components



Compositional and Modular

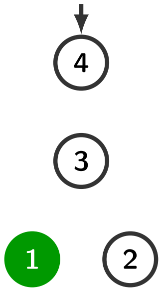
Compositional and modular:

- no abstraction for the leaf components



Compositional and modular:

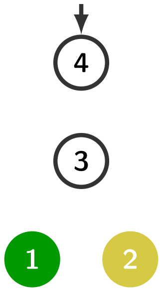
- no abstraction for the leaf components



Compositional and Modular

Compositional and modular:

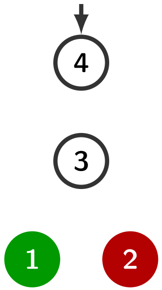
- no abstraction for the leaf components



Compositional and Modular

Compositional and modular:

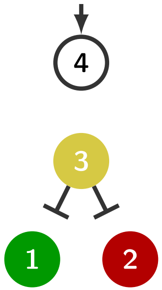
- no abstraction for the leaf components



Compositional and Modular

Compositional and modular:

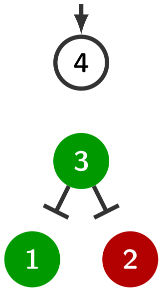
- no abstraction for the leaf components
- as we move up, we abstract subcomponents



Compositional and Modular

Compositional and modular:

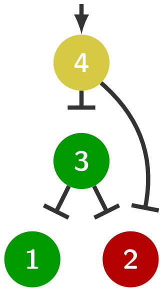
- no abstraction for the leaf components
- as we move up, we abstract subcomponents



Compositional and Modular

Compositional and modular:

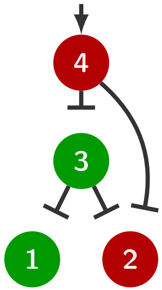
- no abstraction for the leaf components
- as we move up, we abstract subcomponents



Compositional and Modular

Compositional and modular:

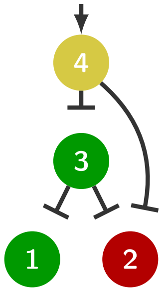
- no abstraction for the leaf components
- as we move up, we abstract subcomponents



Compositional and Modular

Compositional and modular:

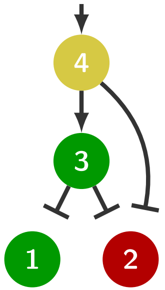
- no abstraction for the leaf components
- as we move up, we abstract subcomponents
  In case of failure we can restart the analysis after refining by removing the abstraction, possibly repeatedly



Compositional and Modular

Compositional and modular:

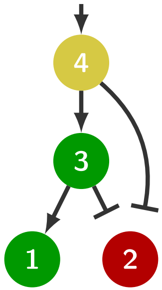
- no abstraction for the leaf components
- as we move up, we abstract subcomponents
  In case of failure we can restart the analysis after refining by removing the abstraction, possibly repeatedly



Compositional and Modular

Compositional and modular:

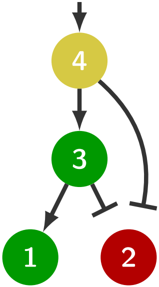
- no abstraction for the leaf components
- as we move up, we abstract subcomponents
  In case of failure we can restart the analysis
  after refining by removing the abstraction,
  possibly repeatedly



Compositional and Modular

Compositional and modular:

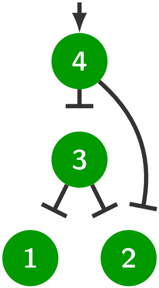
- no abstraction for the leaf components
- as we move up, we abstract subcomponents
  In case of failure we can restart the analysis after refining by removing the abstraction, possibly repeatedly
- all components are checked
- changing subcomponents preserves old results (as long as new versions are correct)
- results for subcomponents are reused
- refining identifies spurious counterexamples



Compositional and Modular: Benefits

If all components are valid, without refinement:

- the system as a whole is correct
- changing a component by a different, correct one does not impact the correctness of the whole system



Compositional and Modular: Benefits

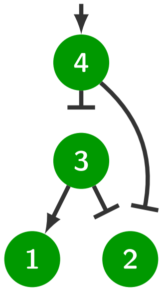
If all components are valid, with refinement:

- the system as a whole is correct
- but the contracts are not good enough for a compositional analysis to succeed

Refinement gives hints as to why

Compositional and Modular: Benefits

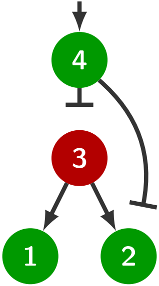
If we had to refine component 1 to prove 3 correct, that's probably because the contract of 1 is too weak



Compositional and Modular: Benefits

If after refining all sub-components we still cannot prove 3 correct, that's because

- the assumptions of 3 are too weak, and/or
- the guarantees of 3 are do not hold



CocoSpec Support

CocoSpec is fully supported by Kind 2 model checker

Kind 2:

- multi-engine SMT-based safety checker for Lustre programs
- competitive with state-of-the-art checkers for infinite-state systems
- engines run concurrently and cooperatively
- can run modular / compositional, mode-aware analysis
- implements all the features discussed so far

References

[1] Adrien Champion, Arie Gurfinkel, Temesghen Kahsai, and Cesare Tinelli. CoCoSpec: A Mode-Aware Contract Language for Reactive Systems. In Proceedings of the 14th International Conference on Software Engineering and Formal Methods (SEFM 2016), Vienna, Austria, 2016. Springer

[2] Kind 2 User Documentation