Validation of Contracts using Enabledness Preserving Finite State Abstractions

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Why contracts?

Software contracts (**pre/postconditions, invariant,...**) appear in a variety of places:

- As a form of early *specification*: Z, "DbC" technique.
- As *annotations* for analysis tools: Spec#, JML for ESC/Java.
- As the *output* of analysis tools: Daikon, DySy.

But understanding contracts is far from being straightforward...

Contracts are hard to validate

contract *CircularBuffer*
  variable a : array [element]
  variable w, r : integer

  invariant : $0 \leq r < |a| \wedge 0 \leq w < |a| \wedge |a| > 3$

  start : $|a| > 3 \wedge r = |a| - 1 \wedge w = 0$

  action *write*(element e)
    pre : $w < r - 1 \vee (w = |a| - 1 \wedge r > 0)$
    post : $r' = r \wedge w' = (w + 1) \% |a| \wedge a' = \text{store}(a, w, e)$

  action element *read*()
    pre : $r < w - 1 \vee (r = |a| - 1 \wedge w > 0)$
    post : $a' = a \wedge w' = w \wedge r' = (r + 1) \% |a| \wedge \text{rv} = a[r']$

Figure: Pre/post specification for a circular buffer

The abstraction we construct

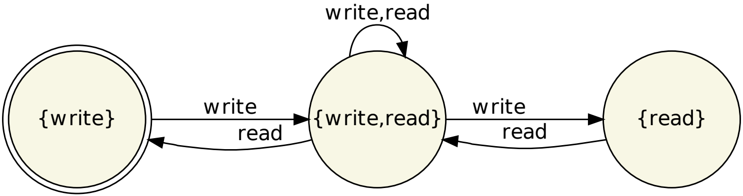

Figure: CircularBuffer contract abstraction

Understanding the CircularBuffer contract

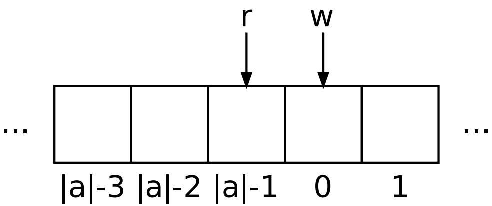

Figure: Empty CircularBuffer

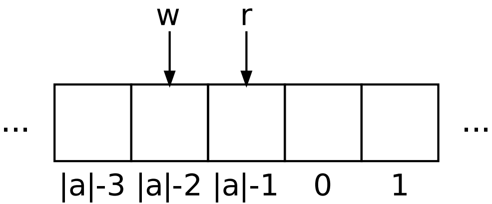

Figure: Full CircularBuffer

What else can we do?

- Prove properties:
  - Can I read from a newly created buffer?
  - Can I read twice from a buffer where I've just written twice?
  - ...

Problem: When do we stop?

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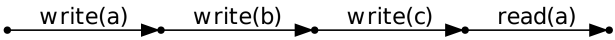

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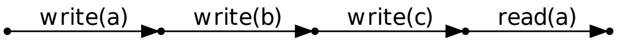

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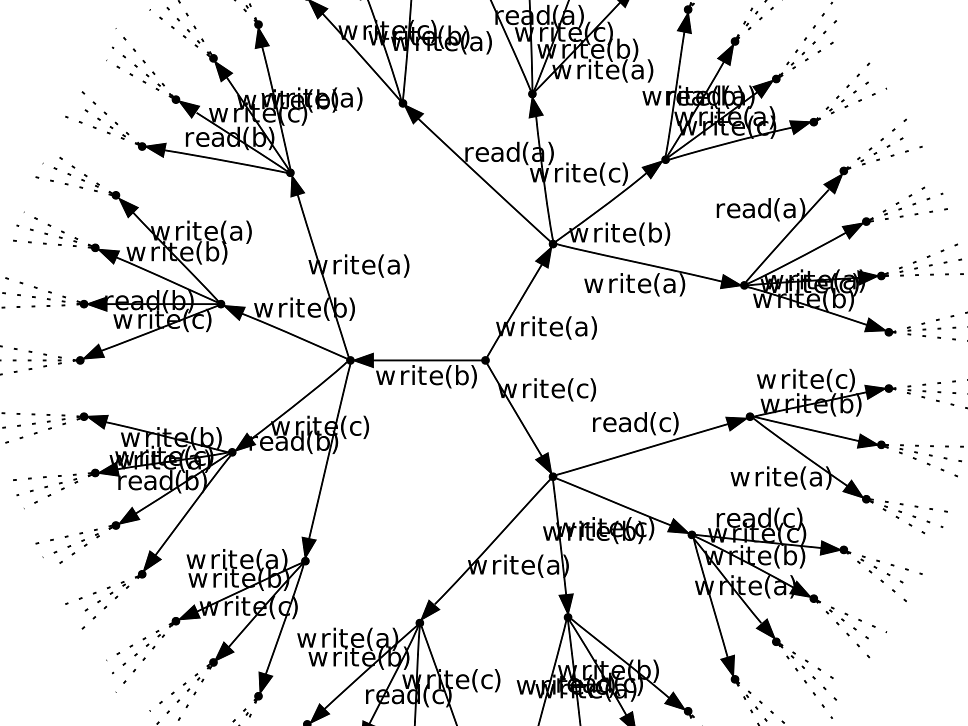

write(a)
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write(c)
read(a)
write(c)
write(b)
write(a)
write(c)
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read(b)
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Simulation is like using a torch light

Figure: It's dark...

Simulation is like using a torch light

Figure: It's dark, we see some lights...

Simulation is like using a torch light

Figure: It's dark, we see some lights, a fountain...

Abstraction is like a pixelized view

Figure: It looks familiar!

Abstraction is the key, but how?

In order to produce an FSM that abstracts the CircularBuffer contract we must deal with:

- Potentially *infinite* parameter values.
- A *non-regular* underlying language.

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- A *non-regular* underlying language.

Precision vs. size (when validating)

We have to be careful when abstracting and...

- avoid creating a lot of states (even infinite) by trying to reduce spurious behaviour.
- avoid creating a trivial abstraction with very few states that produces way too much spurious behaviour.

Enabledness

We need a way to get the "pixelized view" of a contract.

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Enabledness equivalence

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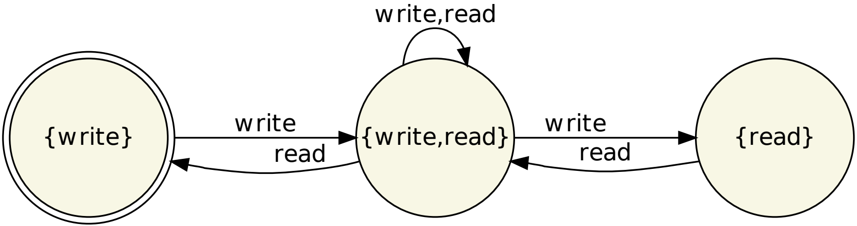

Figure: Enabledness equivalence based abstraction

Formalizing contracts

We say C is a *contract* iff $C = \langle V,\ \text{inv},\ \text{init},\ A,\ P,\ Q \rangle$:

Finite set of variables V

System invariant $\text{inv} \in \mathbb{P}(V)$

Initial predicate $\text{init} \in \mathbb{P}(V)$

Finite set of action labels $A = \{a_1, \ldots, a_n\}$

Preconditions $P : A \rightarrow \mathbb{P}(V \cup \{p\})$

Where p is the (only) action parameter.

Postconditions $Q : A \rightarrow \mathbb{P}(V \cup V' \cup \{p\})$

Where v' denotes the value of v after execution.

Where $\mathbb{P}(X)$ stands for the set of first order logic *predicates* with free variables in X.

Constructing contract abstractions: states

Enabledness-preserving Contract Abstraction (part 1 of 3)

An FSM $M = \langle S,\ S_0,\ \Sigma,\ \delta \rangle$ is an *enabledness-preserving contract abstraction* of $C = \langle V,\ \text{inv},\ \text{init},\ A,\ P,\ Q \rangle$ iff:

1. The set of states is the powerset of actions: $S = 2^A$

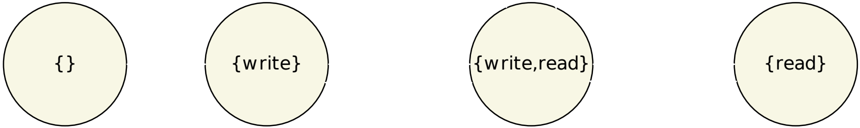

Figure: We use sets of **enabled actions** as states

Constructing contract abstractions: state invariants

State invariant

A state $s \subseteq A$ abstracts system instances on which the **enabled actions** are exactly s, characterized by the *state invariant* inv_s.

$$\mathrm{inv}_s \stackrel{\mathrm{def}}{=} \mathrm{inv} \ \wedge \ \bigwedge_{a \in s} \exists p.\ P_a \ \wedge \ \bigwedge_{a \notin s} \nexists p.\ P_a$$

Figure: We can discard a state s if inv_s is inconsistent.

Constructing contract abstractions: initial states

Enabledness-preserving Contract Abstraction (part 2 of 3)

An FSM $M = \langle S, S_0, \Sigma, \delta \rangle$ is an *enabledness-preserving contract abstraction* of $C = \langle V, \text{inv}, \text{init}, A, P, Q \rangle$ iff:

2. The set of initial states is:

$$S_0 = \{ s \mid \text{init} \Rightarrow \text{inv}_s \}$$

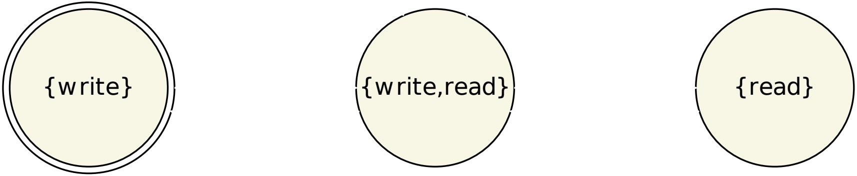

Figure: Initial sets are those implied by the initial predicate

Constructing contract abstractions: transitions

Enabledness-preserving Contract Abstraction (part 3 of 3)

An FSM $M = \langle S,\ S_0,\ \Sigma,\ \delta\rangle$ is an *enabledness-preserving contract abstraction* of $C = \langle V,\ \text{inv},\ \text{init},\ A,\ P,\ Q\rangle$ iff:

3. The alphabet is the set of action labels

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4. The transition function $\delta : 2^A \times A \longrightarrow 2^{2^A}$ satisfies

$$\begin{array}{lll} \delta(s,a) & = \ \emptyset & \text{if } a \notin s \\ \delta(s,a) & \supseteq \ \{s' \mid \text{inv}_s \ \wedge\ Q_a \ \wedge\ \text{inv}'_{s'} \ \text{ is satisfiable}\} & \text{if } a \in s \end{array}$$

(The last item is relaxed due to decidability issues.)

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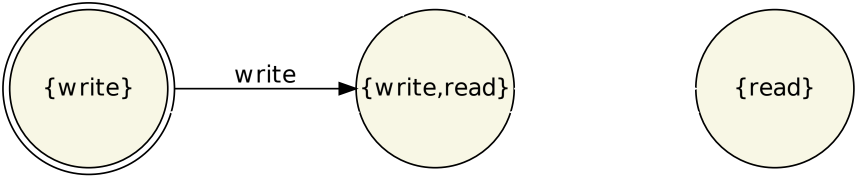

Figure: We add transitions

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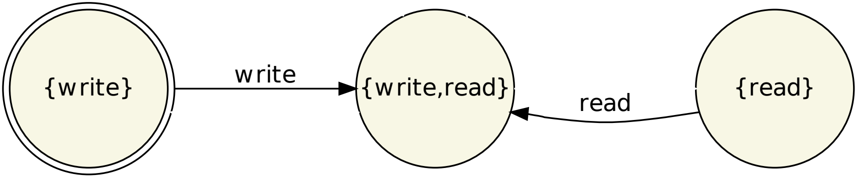

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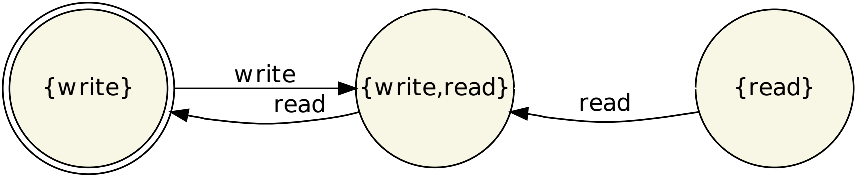

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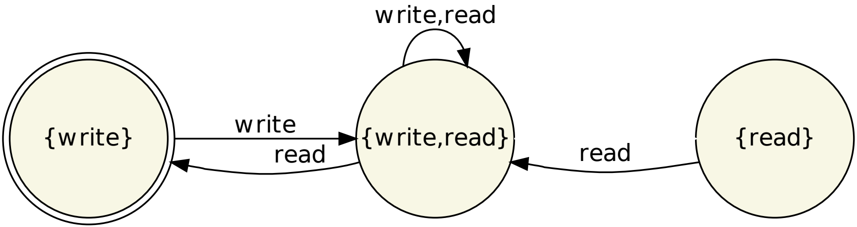

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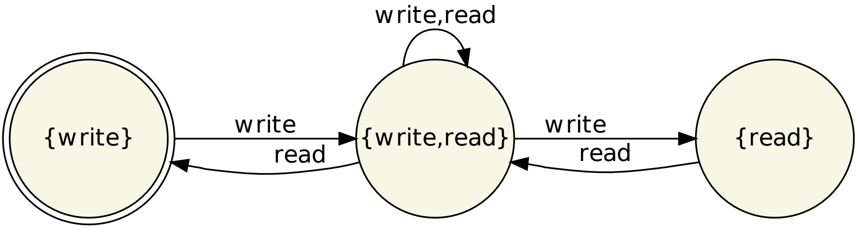

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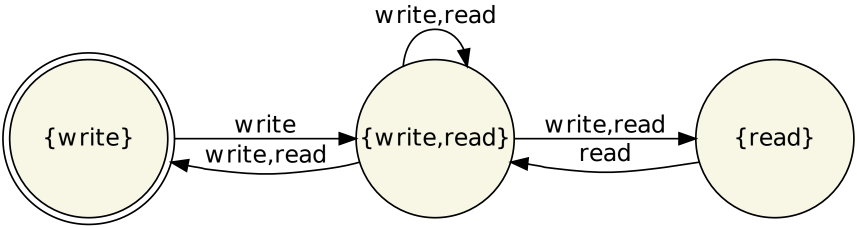

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Validation begins!

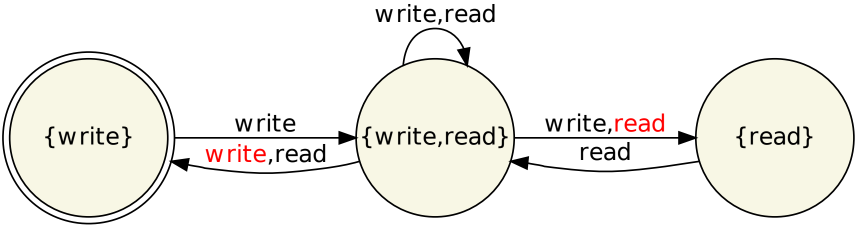

Figure: Finished CircularBuffer contract FSM

What went wrong?

Invariant of state $\{\texttt{write}, \texttt{read}\}$

$$(w < r - 1 \lor (w = |a| - 1 \land r > 0)) \land (r < w - 1 \lor (r = |a| - 1 \land w > 0))$$

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This is consistent with this position of r and w:

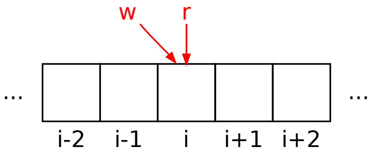

Figure: CircularBuffer with equal pointers

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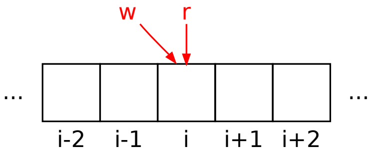

Figure: CircularBuffer with equal pointers

And from this position we can:

- Apply `read()` and go to a full buffer state.
- Apply `write(e)` and go to an empty buffer state.

What did go wrong?

Remember the CircularBuffer contract:

contract *CircularBuffer*
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  variable w, r : integer

  invariant : $0 \leq r < |a| \wedge 0 \leq w < |a| \wedge |a| > 3$

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The contract omitted saying that $r \neq w$ is part of the invariant!

The enabledness-preserving abstraction helped us to find this bug.

Fixed CircularBuffer abstraction

Adding $r \neq w$ to the specification yields:

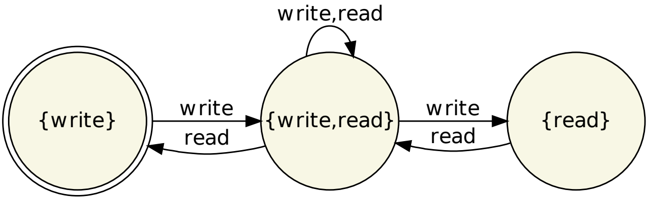


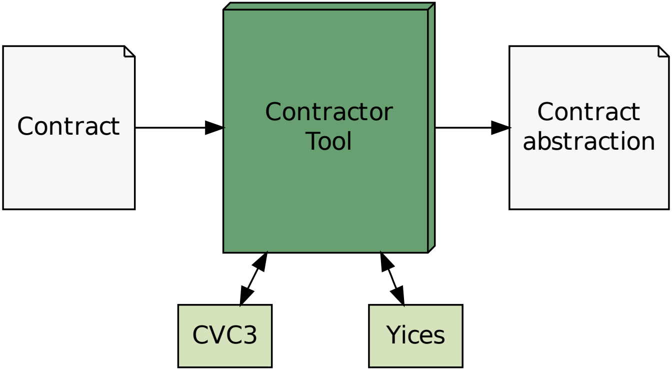
Figure: Finite abstraction of the amended CircularBuffer contract

This abstraction is an intuitive representation of a buffer:

- One state abstracts all the buffers that are empty.
- Other state abstracts all the buffers that are partially full.
- The last state abstracts all the buffers that are full.

Tool support

We implemented a tool called **Contractor**:



Contractor is open source and available at
`http://lafhis.dc.uba.ar/contractor`

Case studies

Using our Contractor tool we were able to carry out a series of case studies, including:

Name	**Source**	**Number of actions**	**Running time**
Web fetcher	DeLine and Fahndrich (ECOOP 2004)	4	0.14 seconds
ATM	Whittle and Schumann (ICSE'00)	8	8 seconds
MS-NSS	Microsoft	13	67 seconds
MS-WINSRA	Microsoft	33	?

Today I will focus on the third one.

The .NET NegotiateStream protocol specification v2.0[1]

.NET NegotiateStream Protocol basics

A protocol for the negotiation of credentials between a client and a server over a TCP stream:

1. The client requests a desired level of security (e.g. encryption).
2. On a first phase a token is passed between the 2 sides.
3. When a special finalization token is received by the client, the second phase starts.
4. During the second phase data is exchanged using the agreed security level.

[1] http://msdn.microsoft.com/en-us/library/cc236723.aspx
Document in version 2.0 during August 2008

Experimental setup

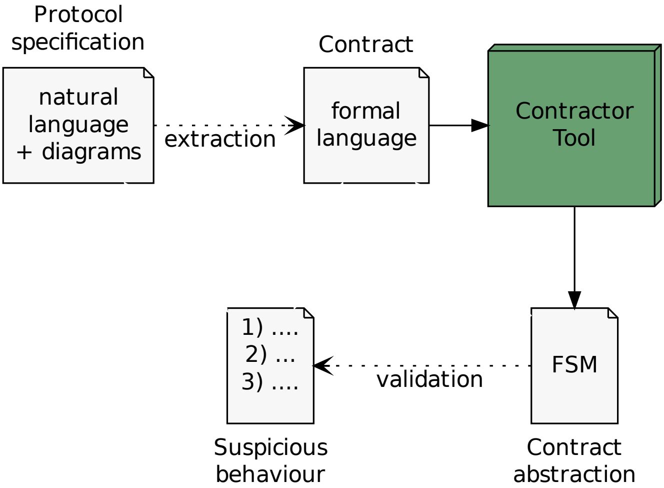


Figure: How the Contractor tool was used

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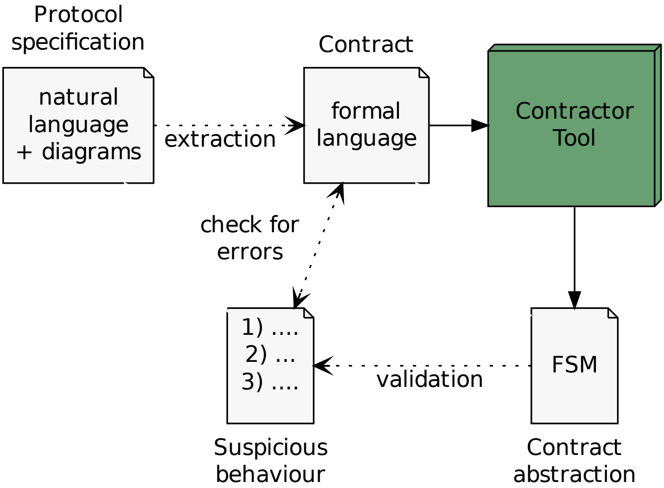

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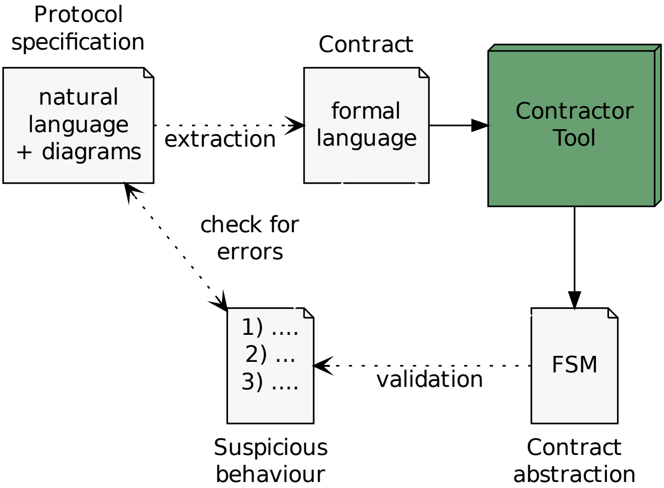

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.NET NegotiateStream finite contract abstraction

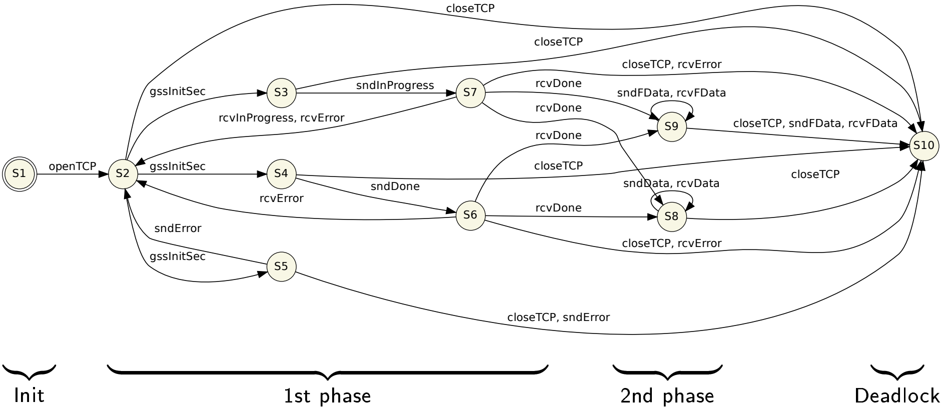


Figure: Finite abstraction of the .NET NegotiateStream protocol contract

.NET NegotiateStream finite: Suspicious behaviour (i)

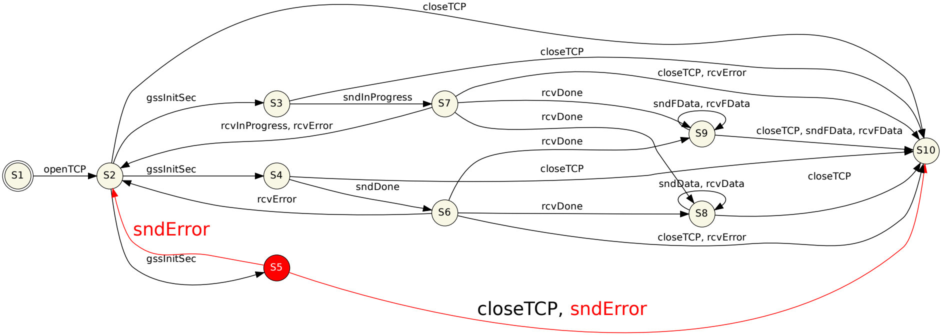
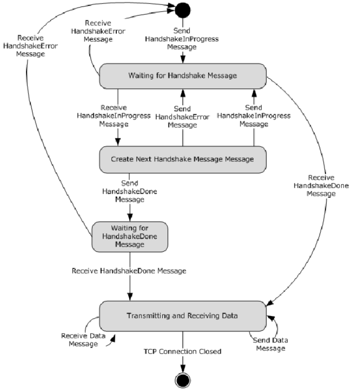
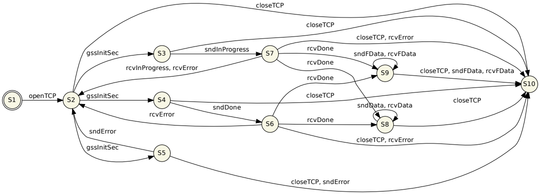


Figure: What happens when error messages occur?

Level of abstraction comparison





These diagrams are not consistent... but *why*?

.NET NegotiateStream finite: Suspicious behaviour (ii)

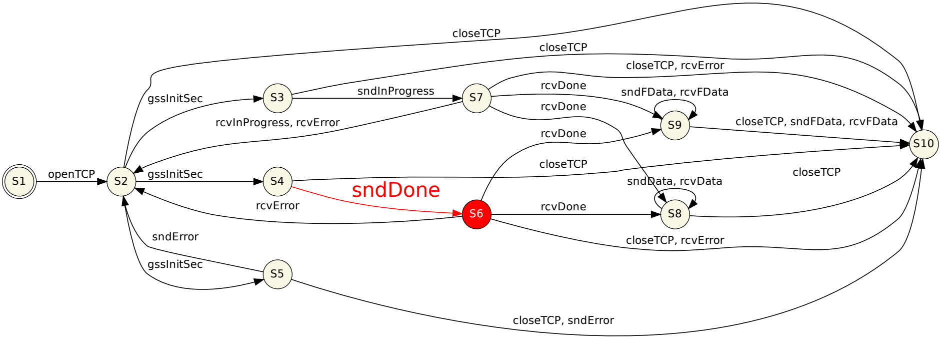


Figure: This FSM deadlocks if composed with the client informal diagram

.NET NegotiateStream finite: Findings

The ambiguities found in the protocol contract abstraction were tracked down in the protocol specification document.

The mentioned errors were corrected in the subsequent official protocol specification.

Contributions

Theoretical

- We formalised the concept of enabledness-based finite behavioural contract abstractions.
- We provided a novel symbolic algorithm to get such abstractions.

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Theoretical

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- We provided a novel symbolic algorithm to get such abstractions.

Practical

- We showed their potential validation capacity.
- We implemented our algorithm as a practical tool and used it on a variety of contracts.
- We discovered inconsistencies or omissions in real-life specifications.

Current and future work

Scalability We're working on an on-the-fly multi-threaded algorithm.

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Precision We would like to distinguish transitions depending on whether they are always traversable or not. Modalities.

Analysability Add simulation support to the tool, together with visual aids such as a hierarchical view of states or decomposition into smaller FSMs.

Related work (i): predicate abstraction

- **Sun and Dong**[2].
  Construction of states using predicates from LSCs and transitions using pre/postconditions.
- **Grieskamp, Kicillof and Tillmann**[3]. **Nebut, Fleurey, Le Traon and Jézéquel**[4]. **Leuschel and Butler**[5].
  Exploration of a contract state space symbollicaly or concretely but no intention to construct a finite abstraction.
- **Van, van Lamsweerde, Massonet and Ponsard**[6].
  Construction of a contract finite abstraction by imposing bounds to the data domains.

---

[2] *Design synthesis from interaction and state-based specifications*, TSE 2006

[3] *Model-based quality assurance of Windows protocol documentation*, ICST 2008

[4] *Automatic test generation: a use case driven approach*, TSE 2006

[5] *ProB: an automated analysis toolset for the B method*, STTT 2008

[6] *Goal-oriented requirements animation*, RE 2004

Related work (ii): other techniques

- **Lee and Yannakakis**[7]. **Tripakis and Yovine**[8].
  Minimisation of LTSs by stabilising state space partitions. Requiring pre-stability may end up in huge or even infinite LTSs in our setting.
- **Alur, Cern, Madhusudan and Nam**[9].
  Conservative construction of finite behaviour models out of Java code. By avoiding exception raising the result is too restrictive when the system language is non-regular.
- **Gabel and Su**[10].
  Mining of finite state automata out of execution traces.
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Thank you!

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