Transforming Medical Best Practice Guidelines to Executable and Verifiable Statechart Models

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Outline

1. Introduction
2. Transforming Yakindu Statechart to UPPAAL Timed Automata
3. Trace Failed UPPAAL Properties back to Yakindu Statecharts
4. Cardiac Arrest Case Study
5. Conclusion

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Medical Guidelines

- Medical best practice guidelines play an important role in improving effectiveness and safety of medical care.
- The existing medical best practice guidelines in hospital handbooks are often lengthy and difficult for medical staff to remember and apply clinically.
- The text-based best practice guidelines are represented and encoded into many computer interpretable formats, such as Asbru, GLIF, PROforma, etc.
- However, those formats are not user friendly for physicians to validate their correctness.
- Furthermore, it is not easy to formally verify those formats for life-critical medical cyber-physical systems.

Statecharts

Statechart has several advantages:

- have high similarity to disease models and treatment models
- allow quick clinical validations with medical doctors
- executable
- enable rapid prototyping
- widely used in modeling complex systems

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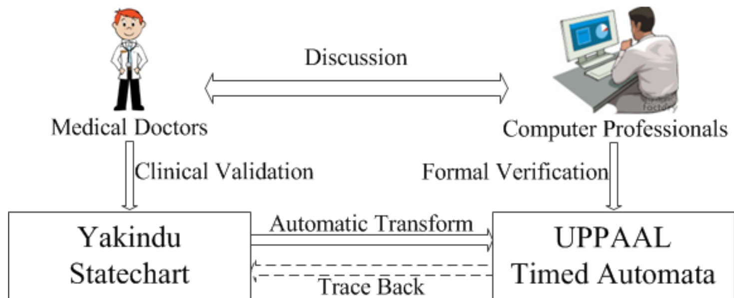
However, clinical validation is often not adequate for guaranteeing the correctness and safety of medical guideline models, and formal verification is required.

Guidelines to Verifiable Statecharts

We propose an approach that transforms medical best practice guidelines to verifiable statechart models and supports both clinical validation and formal verification.



Guidelines to Verifiable Statecharts

Why choose Yakindu statechart tool to model medical best practice guidelines?

1. The Yakindu statechart tool has a well-designed user interface and has simulation and code generation functionality, which enables rapid prototyping and validation with medical staff.
2. Yakindu statechart tool is an open-source tool kit, which can be customized according to medical domain knowledge.

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Why choose UPPAAL to verify guideline statecharts?

1. The structure of UPPAAL time automata and Yakindu statechart are similar, which makes the transformation and trace back easier.
2. UPPAAL has a graphical user interface and has simulation and counter example generation functionality, which advances model debug.

Guidelines to Verifiable Statecharts

Why not encode best practice guidelines to UPPAAL timed automata directly?

1. According to discussion with medical staff, Yakindu is easier for them to understand and use.
2. UPPAAL does not provide code generation functionality, therefore, system designers must manually translate timed automata to executable code, which is error-prone.

Guidelines to Verifiable Statecharts

- Due to syntax and semantics differences, to bridge the gap between Yakindu and UPPAAL models is a challenge.
- Our strategies are to build transformation rules for each element used in the two models and use these rules as the foundation for the transformation.

Guidelines to Verifiable Statecharts

- Due to syntax and semantics differences, to bridge the gap between Yakindu and UPPAAL models is a challenge.
- Our strategies are to build transformation rules for each element used in the two models and use these rules as the foundation for the transformation.
- We develop the Y2U tool to transform the Yakindu statechart to UPPAAL timed autoamta and to trace back failed medical properties.
- The tool is available on `www.cs.iit.edu/~code/software/Y2U`.

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Yakindu Statecharts vs UPPAAL Timed Automata

Differences between Yakindu statecharts and UPPAAL timed automata:

1. Syntax: they have different syntactic element sets
2. Structure: Yakindu supports hierarchical structure, while UPPAAL only supports flat structure
3. Execution Semantics: Yakindu model is deterministic and has synchronous execution semantics while the execution of UPPAAL model is non-deterministic and asynchronous
4. Simultaneous Events: Yakindu supports simultaneous events while UPPAAL model does not

Transformation Principles

- **Principle I**: must have equivalent execution semantics
- **Principle II**: must maintain Yakindu syntactic elements when possible
- **Principle III**: should introduce minimal additional elements from the Yakindu model

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Principle I ensures that verification results from UPPAAL hold in the Yakindu model.

Principle II and **Principle III** ensure that an execution path in UPPAAL model can be traced back to the Yakindu model with reduced complexity.

Transformation Rules

Transformation rules to bridge four type differences between Yakindu statecharts and UPPAAL timed automata:

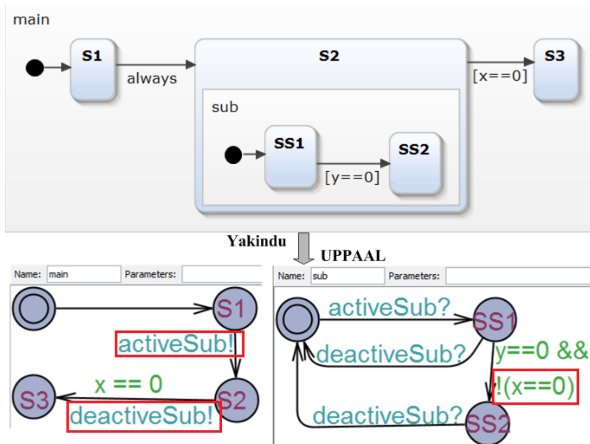
1. Syntax: **Rule 1** to **Rule 6** for basic elements of Yakindu statecharts
2. Structure: **Rule 7** to flatten hierarchical structure
3. Execution Semantics: **Rule 8** to **Rule 9** to model determinism and synchrony with UPPAAL
4. Simultaneous Events: **Event Stack** to support simultaneous events in UPPAAL

Transformation Rules: Syntax

- **Rule 1: State**
- **Rule 2: Transition**
- **Rule 3: Data Type**
- **Rule 4: Event**
- **Rule 5: Timing Trigger**
- **Rule 6: State Action**

Transformation Rules: Structure

- **Rule 7: Composite State**



Transformation Rules: Execution Semantics (1)

Yakindu statecharts execution semantics:

- Internal Determinism of an Automaton: transition priority (**Rule 8**)
- External Determinism among Automata: automaton priority (**Rule 9**)
- Synchrony: synchronous execution (**Rule 9**)

Transformation Rules: Execution Semantics (2)

- **Rule 8: Transition Priority**
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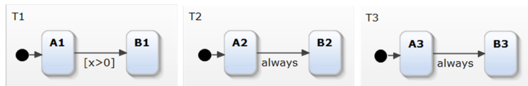
- **Rule 8: Transition Priority**
  - Adjust transition guard to simulate transition priorities
- **Rule 9: Automaton Priority and Synchrony**
  - Use the lockstep method to force synchronous execution based on automaton priorities.
  - Each automaton is associated with an integer to indicate how many steps the automaton has executed. (How to solve out-of- range problem of step indicators?)
  - Add an additional guard on execution step indicator to each transition. (How to solve deadlock problem caused by additional guards?)

Transformation Rules: Simultaneous Events

- **Event Stack**
  1. An automaton can raise and accept multiple events at the same time
  2. Multiple automata can accept the same event concurrently
  3. An event can only be accepted by automata with lower priorities than the automaton which raise the event
  4. An event can only be accepted in the same execution time cycle in which it is raised

To transform a Yakindu model, we may combine multiple transformation rules.



Transformation Correctness

We define a Yakindu model and its associated transformed UPPAAL model are equivalent if their observable executions are equivalent, i.e.,

1. the two models have the same execution path if the input settings are the same
2. all variable values at each execution step of the two models are equal

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Theorem

*The UPPAAL model transformed from a given Yakindu model by applying **Rule 1** to **Rule 9** maintains the Yakindu model's execution behaviors.*

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Mapping between Yakindu and UPPAAL Models

- **Rule 4** and **Rule 5** add auxiliary event automata and timer automata to the UPPAAL model.

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- **Rule 4** and **Rule 5** add auxiliary event automata and timer automata to the UPPAAL model.
- However, the added automata does not affect the model's execution behaviors.
- Hence, we ignore these added events and timer automata when tracing back execution path from UPPAAL to Yakindu.

Mapping between Yakindu and UPPAAL Models

Theorem

Given a Yakindu model Y and its transformed UPPAAL model U (with auxiliary event and timer automata being removed), the mapping from UPPAAL state set $\mathcal{S}_U$ to Yakindu state set $\mathcal{S}_Y$ is bijective.

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Theorem

Given a Yakindu model Y and its transformed UPPAAL model U (with auxiliary event and timer automata being removed), the mapping from UPPAAL transition set $\mathcal{T}_U$ to Yakindu transition set $\mathcal{T}_Y$ is surjective, but not injective.

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- **Rule 6**, **Rule 7**, and **Rule 9** add transitions into $\mathcal{T}_U$.

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- **Rule 6**, **Rule 7**, and **Rule 9** add transitions into $\mathcal{T}_U$.
- However, our analysis shows that the back trace of the added transitions can be ignored.

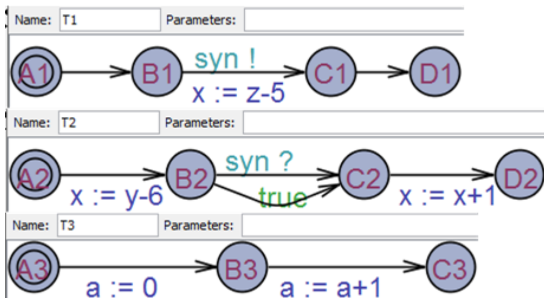
Trace Back Procedure

1. Delete the additional event automata added by **Rule 4** and timer automata added by **Rule 5** in the given UPPAAL execution path.
2. For each state in the path, find its corresponding state in Yakindu model.
3. For each transition in the path, find its corresponding transition in Yakindu model; if the corresponding transition is not found in the Yakindu model, ignore the transition.

Trace Back Example

Example

Given a Yakindu model whose transformed UPPAAL model is shown below, verify the property $A[\,]$ `T2.D2 imply` $x > 0$.



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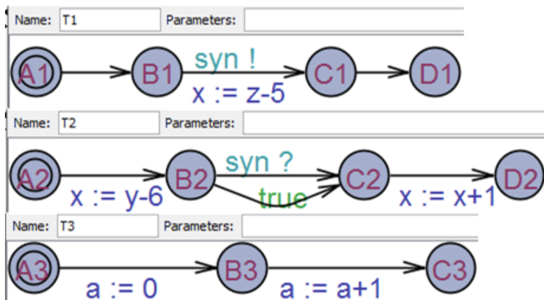


The property is not satisfied.

Trace Back Example (cont.)

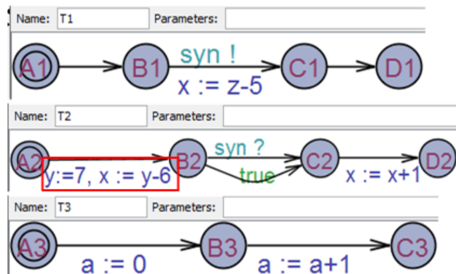
Example

Counter Example:

$(\mathtt{A1}, \mathtt{A2}, \mathtt{A3}) \rightarrow (\mathtt{A1}, \mathtt{B2}, \mathtt{A3}) \xrightarrow{\mathtt{true}} (\mathtt{A1}, \mathtt{C2}, \mathtt{A3}) \rightarrow (\mathtt{A1}, \mathtt{D2}, \mathtt{A3})$

Yakindu Model Fix:

the action of transition $\mathtt{A2} \rightarrow \mathtt{B2}$ to $y := 7, x := y - 6$



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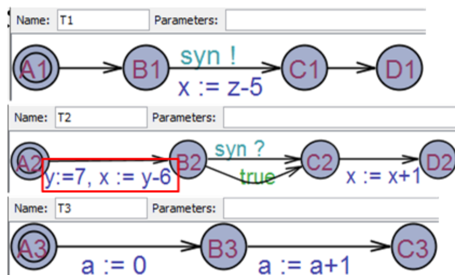

The property still does not hold.

Trace Back Example (cont.)

Example

Counter Example: $(\texttt{A1}, \texttt{A2}, \texttt{A3}) \rightarrow (\texttt{A1}, \texttt{A2}, \texttt{B3}) \rightarrow (\texttt{B1}, \texttt{A2}, \texttt{B3}) \rightarrow (\texttt{B1}, \texttt{B2}, \texttt{B3}) \xrightarrow{\texttt{syn}} (\texttt{C1}, \texttt{C2}, \texttt{B3}) \rightarrow (\texttt{C1}, \texttt{D2}, \texttt{B3})$

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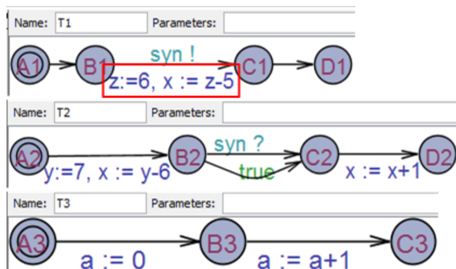

Trace Back Example (cont.)

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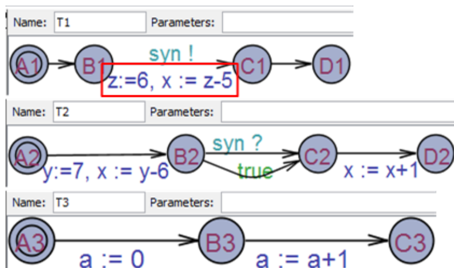

The property now is satisfied. In this example, two iterations are taken to fix the errors in the model.

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Cardiac Arrest Case Study

A simplified cardiac arrest treatment scenario is used as a case study to validate the proposed medical guidelines transforming approach.

- Use Yakindu to model the simplified cardiac arrest treatment procedure.
- Inject an error into the Yakindu model.
- Transform the model built with Yakindu to UPPAAL model with the Y2U tool.
- Verify two medical properties in the transformed UPPAAL model. One property is satisfied, the other one is failed.

Cardiac Arrest Case Study (cont.)

- Trace the failed property back to the Yakindu model and modify the Yakindu model.
- Re-transform the modified Yakindu model and re-verify the two medical properties. Both properties are satisfied.

Cardiac Arrest Case Study (cont.)

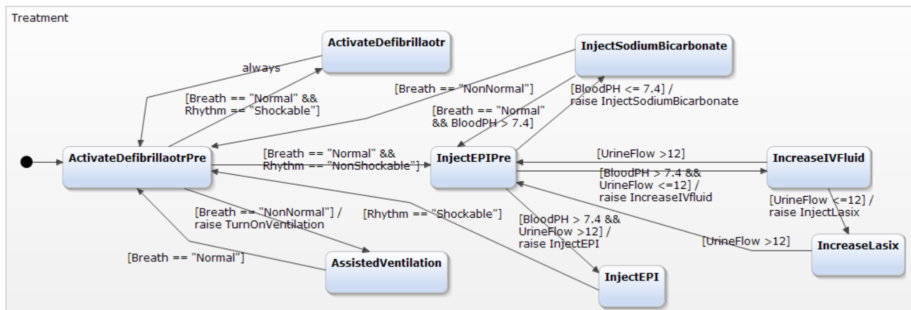

Figure: Cardiac Arrest Treatment Yakindu Model

Cardiac Arrest Case Study (cont.)

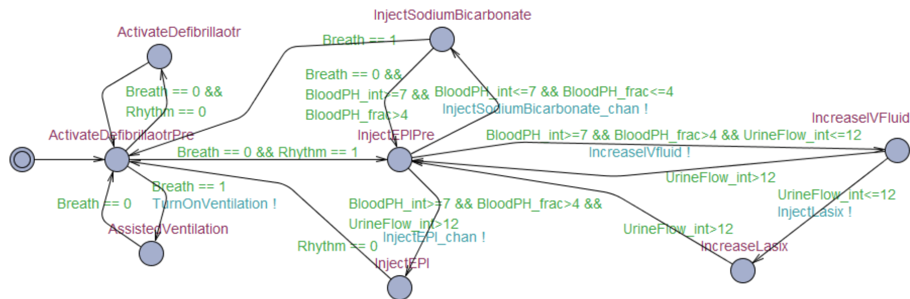

Figure: Cardiac Arrest Treatment UPPAAL Model

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Conclusion

- The paper presents an approach to transform medical best practice guidelines to executable and verifiable statechart models.
- We develop the Y2U tool to transform a statechart model to a verifiable formal model.
- The designed transformation rules not only maintains the execution equivalence between the statechart model and the formal model, but also allow easy trace back of failed medical properties to the statechart model.
- A simplified cardiac arrest treatment scenario is used as a case study to validate the proposed approach.
- The tool is available on `www.cs.iit.edu/~code/software/Y2U`.

Acknowledgement

We thank Mohammad Hosseini and Maryam Rahmaniheris for their valuable suggestions to the Y2U tool.

The research is supported in part by NSF CNS 1545008 and NSF CNS 1545002.

Questions?

Thank You

Transformation Rules: Syntax (1)

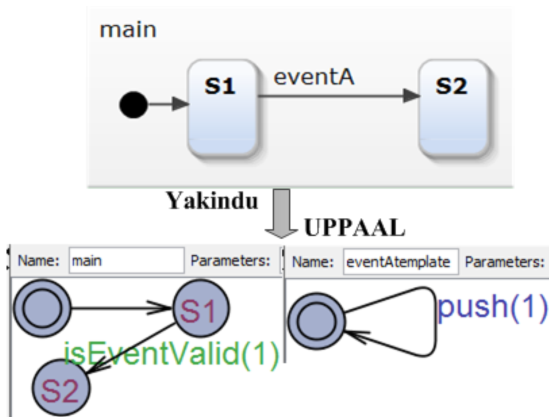
- **Rule 1: State**
  - *state* $\longrightarrow$ *state*
- **Rule 2: Transition**
  - *transition* $\longrightarrow$ *transition*

Transformation Rules: Syntax (1)

- **Rule 1: State**
  - *state* $\longrightarrow$ *state*
- **Rule 2: Transition**
  - *transition* $\longrightarrow$ *transition*
- **Rule 3: Data Type**
  - Real Number: two integers to store its integer part and fraction part, respectively
  - String: an integer variable with a dictionary

Transformation Rules: Syntax (2)

- **Rule 4: Event**



- **Rule 5: Timing Trigger**

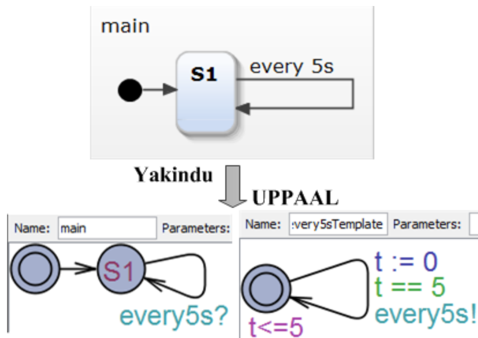


Figure: *Every* Timer Transformation

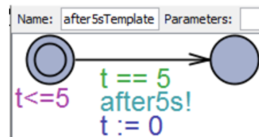
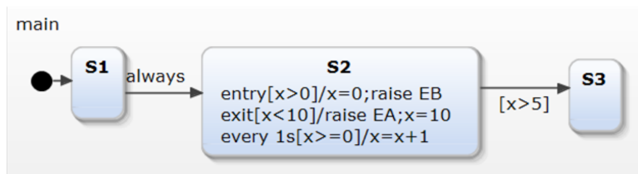


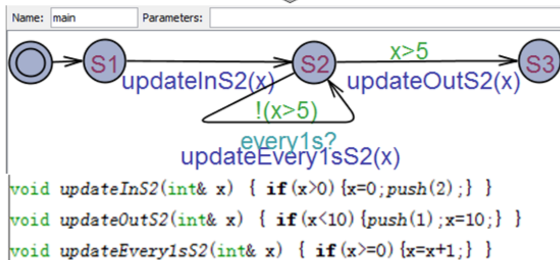
Figure: *After* Timer Automaton

Transformation Rules: Syntax (4)

- **Rule 6: State Action**



Yakindu
UPPAAL



Transformation Rules: Execution Semantics (2)

- **Rule 8: Transition Priority**
  - a state has n outgoing transitions $\{T_1, T_2, \ldots, T_n\}$ sorted in non-increasing priority order
  - the original guard of transition T_i is denoted as G_i
  - the transition guard for T_i is adjusted to be G_i && $!G_1$ && $!G_2$ && ... && $!G_{i-1}$

Transformation Rules: Execution Semantics (3)

- **Rule 9: Automaton Priority and Synchrony**
  - Use the lockstep method to force synchronous execution based on automaton priorities.
  - Suppose a model contains n automata $\{A_1, A_2, \ldots, A_n\}$ that are sorted by its execution priority in decreasing order.
  - Each automaton A_j is associated with an integer I_j to indicate how many steps A_j has executed.
  - For each state in A_j, we add a self-loop transition which is guarded by the negation of all existing outgoing transition guards of the state.

Transformation Rules: Execution Semantics (4)

- **Rule 9: Automaton Priority and Synchrony** (cont.)
  - For each transition in A_j, we add an additional guard on execution step indicator I_j, which is conjuncted with the existing guard to force synchronous execution.
    - A_1: $I_1 == I_2$ && $I_2 == I_3$ && $\ldots$ && $I_{n-1} == I_n$
    - A_j ($j > 1$): $I_j < I_{j-1}$
  - I_j is increased by 1 when A_j executes one step.
  - When the automaton with the lowest priority executes a transition, it clears all events for current time cycle.