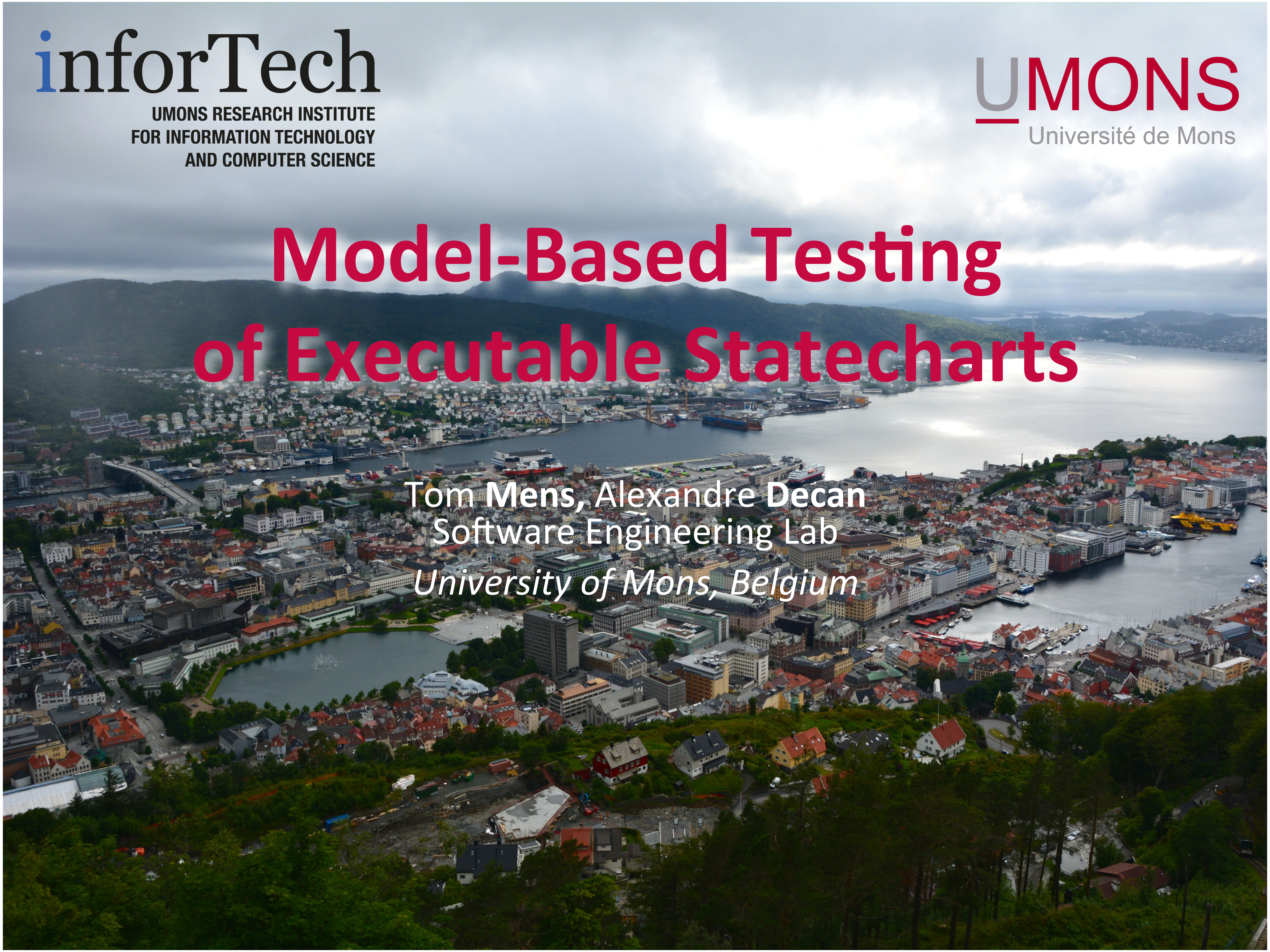

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Model-Based Testing of Executable Statecharts

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Agile and defensive development

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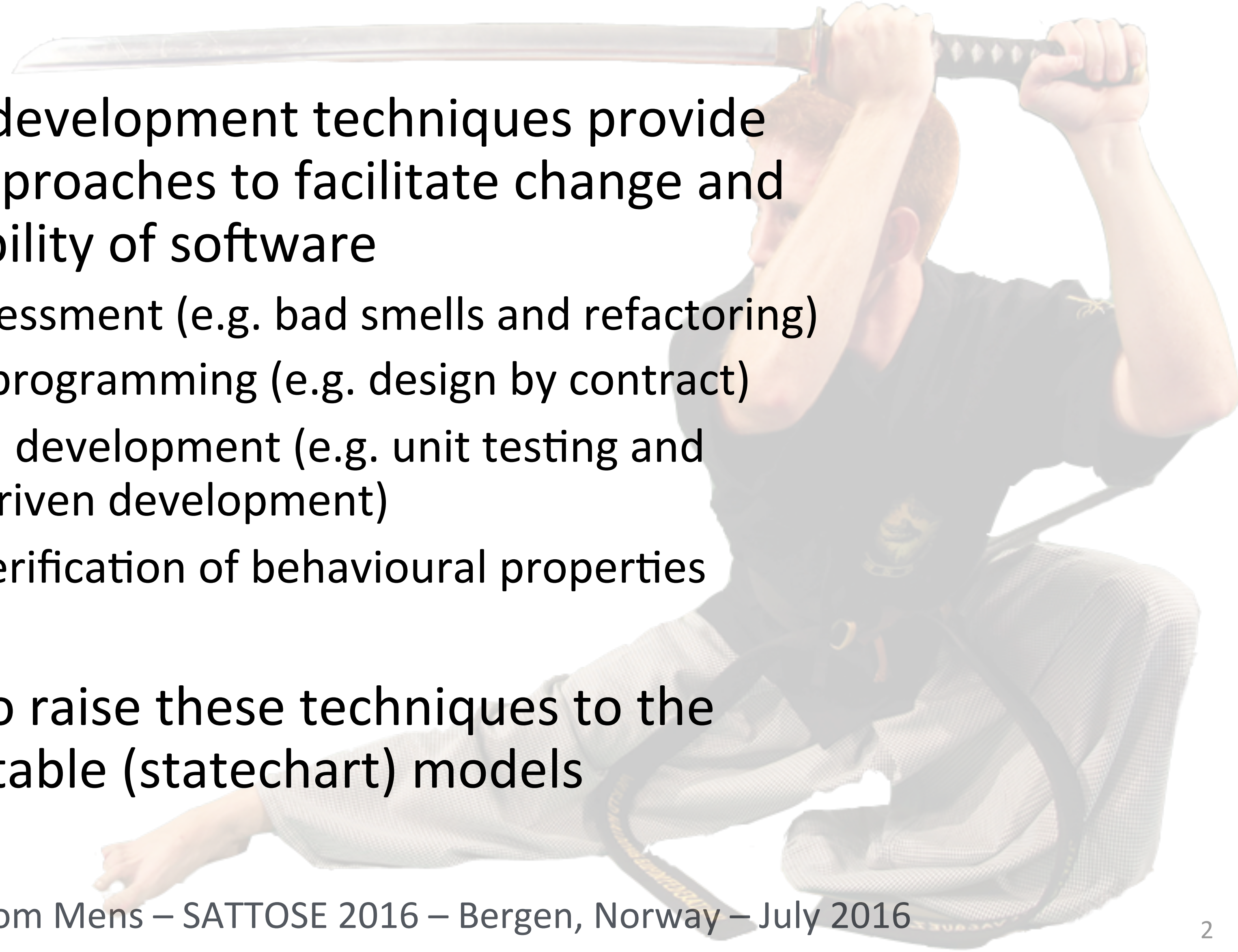

Many "agile" development techniques provide lightweight approaches to facilitate change and increase reliability of software

- Quality assessment (e.g. bad smells and refactoring)
- Defensive programming (e.g. design by contract)
- Test-driven development (e.g. unit testing and behavior-driven development)
- Dynamic verification of behavioural properties

We propose to raise these techniques to the level of executable (statechart) models

Future work (spoiler)

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Facilitate evolution of behavioural design models

- Detecting model smells
- Model refactoring
  - E.g. splitting up a complex statechart into multiple statecharts
- Semantic variation
  - Detecting if statechart is compatible with alternative semantics
- Variability analysis
  - Consider product families (e.g. different microwave variants) and analyse commonalities and variabilities in their statechart models
- Design space exploration
  - Analyse pros and cons of syntactically different, but semantically similar statecharts

Agile and defensive modelling

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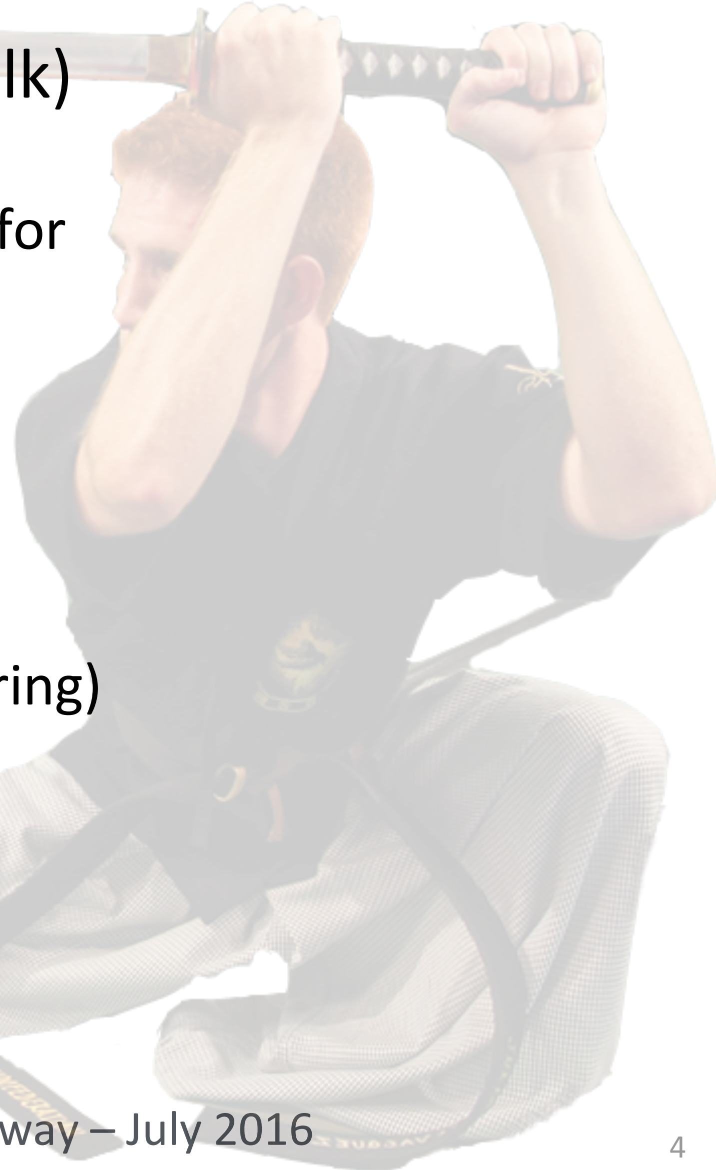

- Advanced model testing (focus of this talk)
  - Contract-driven modeling
  - Test-driven modeling (unit testing and BDD for statecharts)
  - Dynamic verification (property statecharts)

- Future work
  - Model quality assessment (model smells)
  - Model quality improvement (model refactoring)
  - Model checking
  - Model variability analysis
  - Design space exploration
  - Model composition and scalability
  - Semantic variation

Running example

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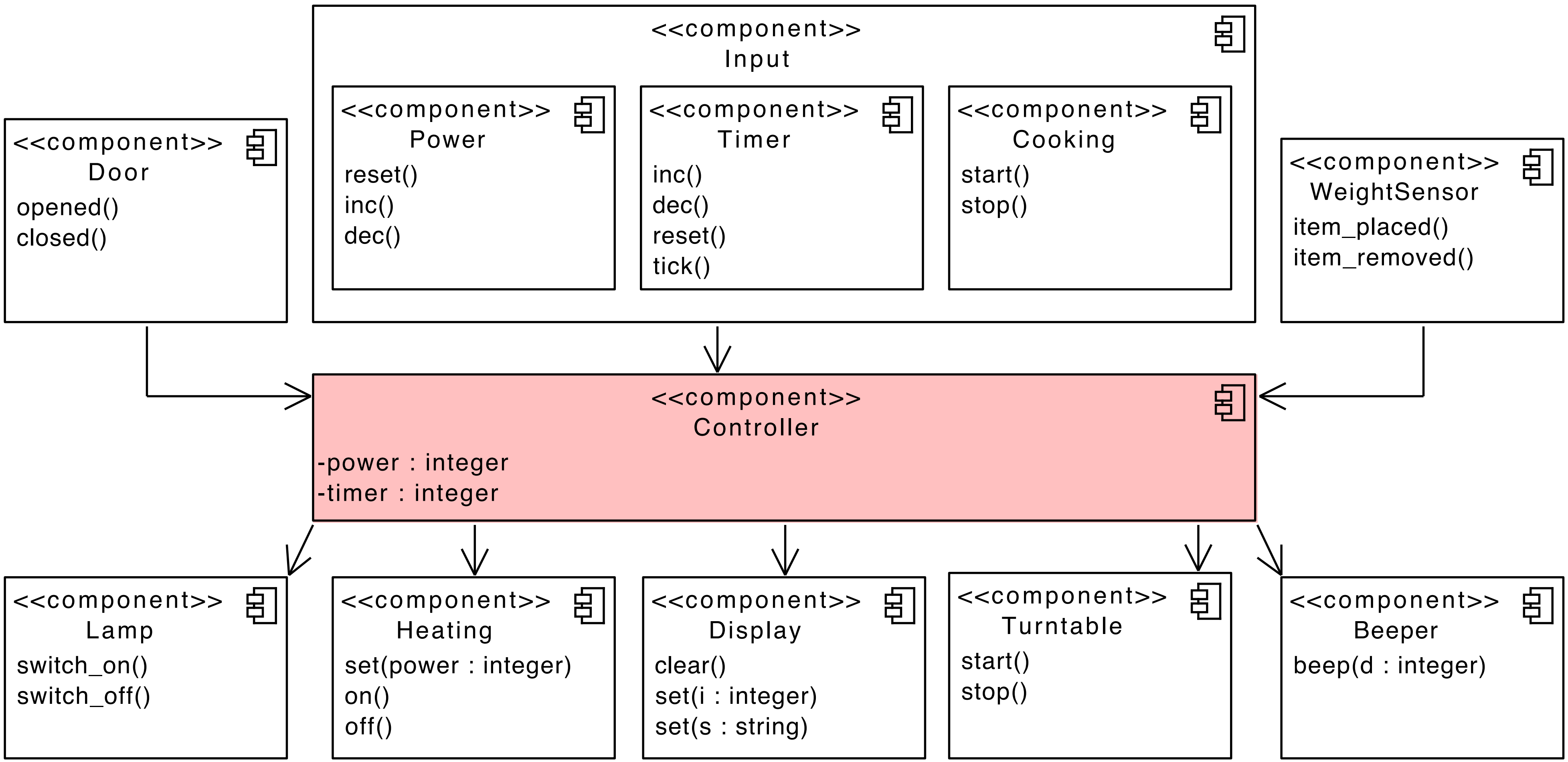
Microwave oven



Running example

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Use case name : Cook Food
Summary : User puts food in oven, and oven cooks food.
Assumptions : Oven has been configured with weight sensor and turntable.

Preconditions : Oven is closed and empty.

Postconditions : Oven has cooked the food. Oven is closed and empty.

Basic course of action :

1. User opens door.
2. User puts food in oven and closes door.
3. User sets cooking time via control panel.
4. User presses start button.
5. Magnetron indicator light switches on. Magnetron starts cooking food.
6. Remaining cooking time is displayed continuously.
7. System notifies user when cooking time has elapsed. Magnetron indicator light switches off.
8. User opens door, removes food from oven, and closes door.
9. System clears display and resets default values for cooking.

Running example

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Use case name : Cook Food

Alternate courses:

1a : User presses start button while door is open. System does not start cooking.

3a : User presses start button while no food is in the oven. System does not start cooking.

3b : User presses start button while cooking time is zero. System does not start cooking.

5a : User opens door during cooking. Magnetron stops and indicator light turns off. User removes food, closes door and presses Stop. Go to step 9.

5b : User opens door during cooking. Magnetron stops and indicator light turns off. User closes door and presses Start to resume cooking. Go to step 5.

5c : User presses Stop during cooking. Magnetron stops and indicator light turns off. User presses Start to resume cooking. Go to step 5.

Running example

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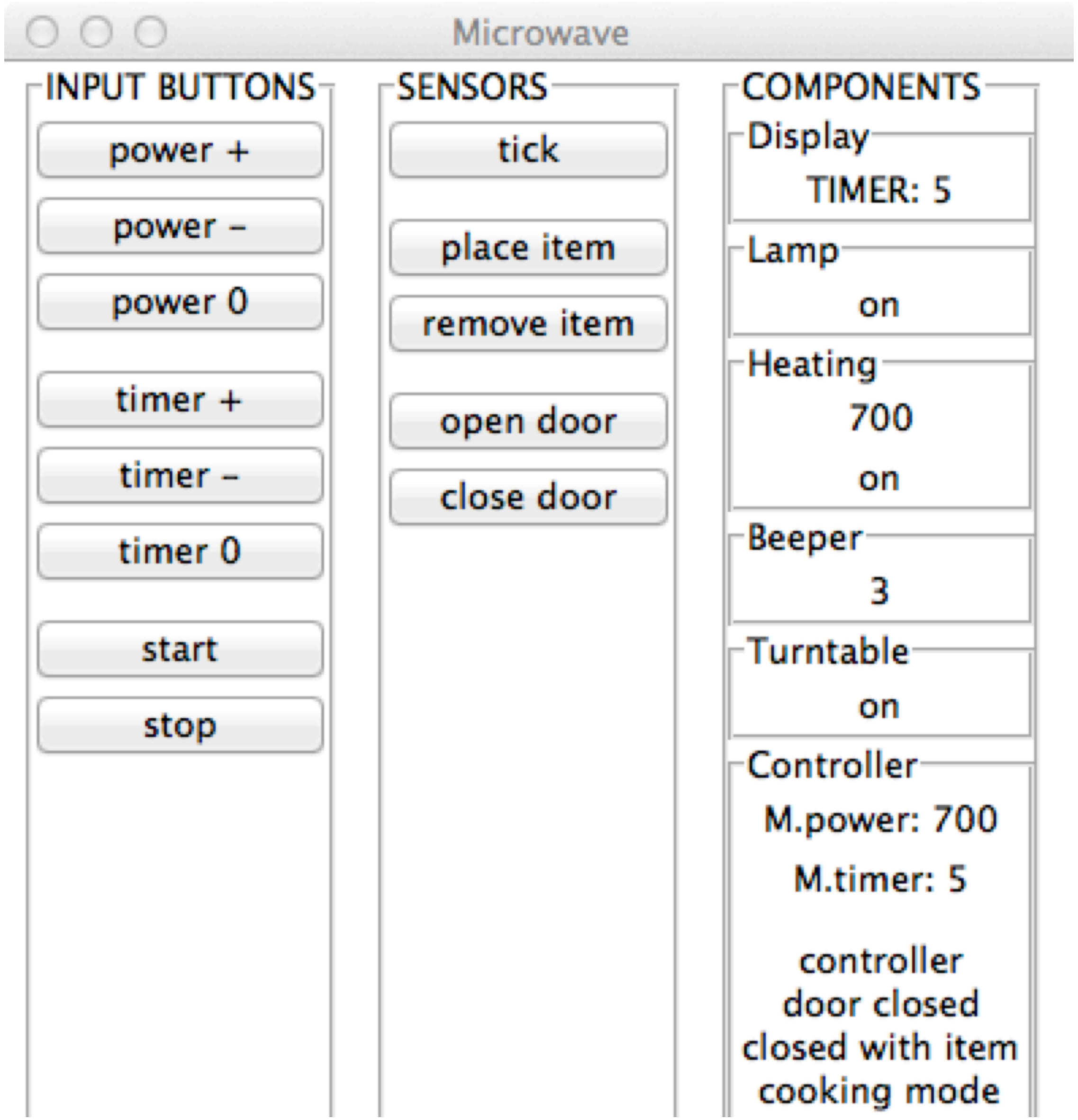
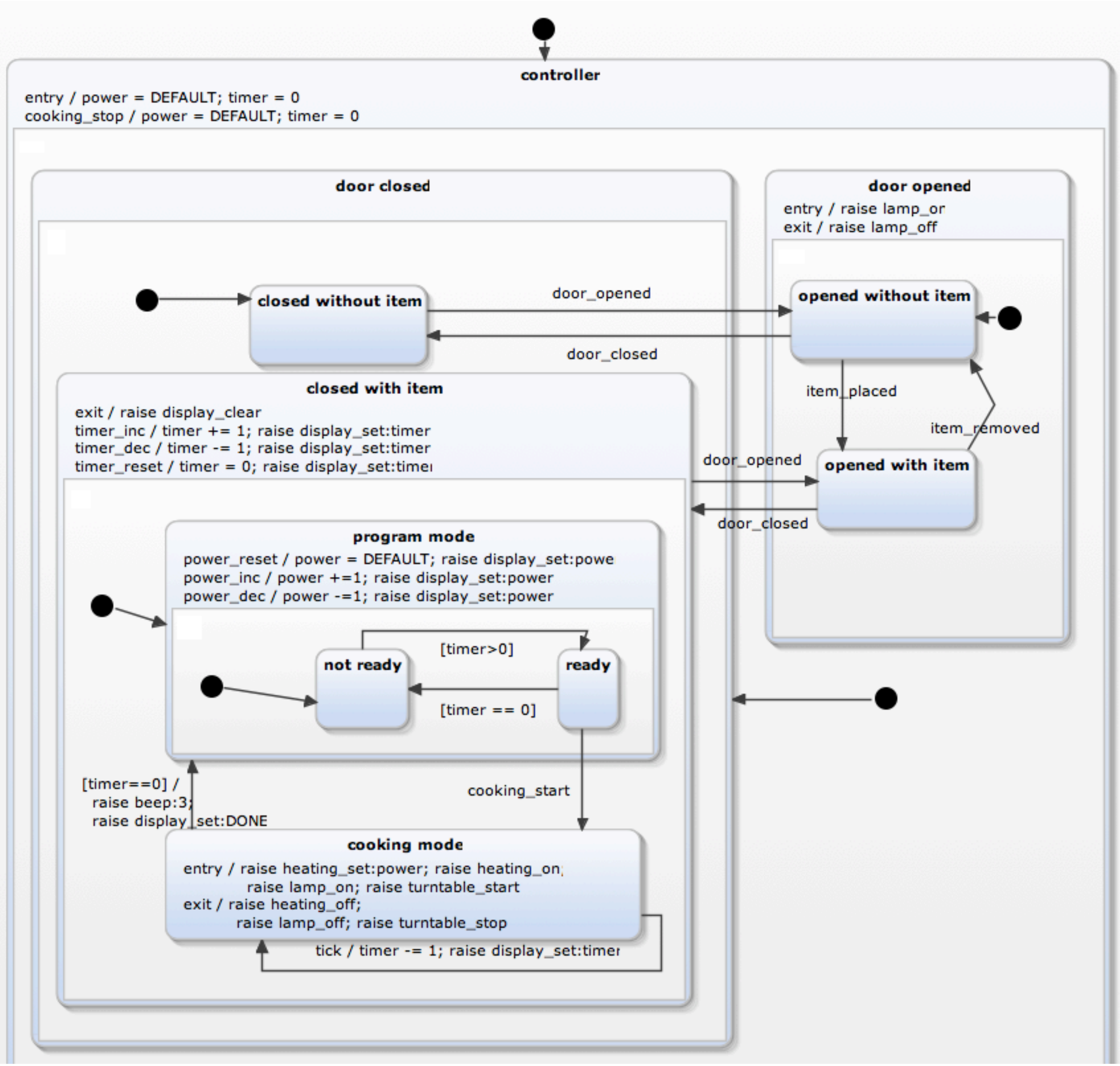
Microwave oven



Oven controller statechart



Software-controlled systems are *difficult to develop*

Control software can be very ***complex***

- Continuous interaction between software and hardware
- Continuous interaction with external world and users
- Must respect *functional* requirements
  - Oven should cook food placed in oven with specified power and duration
- Must respect *non-functional* requirements
  - Oven should stop sending microwaves if doors are opened

Contract-driven development

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- Add precise and dynamically verifiable specifications to executable software components (e.g., methods, functions, classes)
- Based on Bertrand Meyer's "*Design by Contract*"
- The software compoment should respect a *contract*, composed of
  - *preconditions*
  - *postconditions*
  - *invariants*

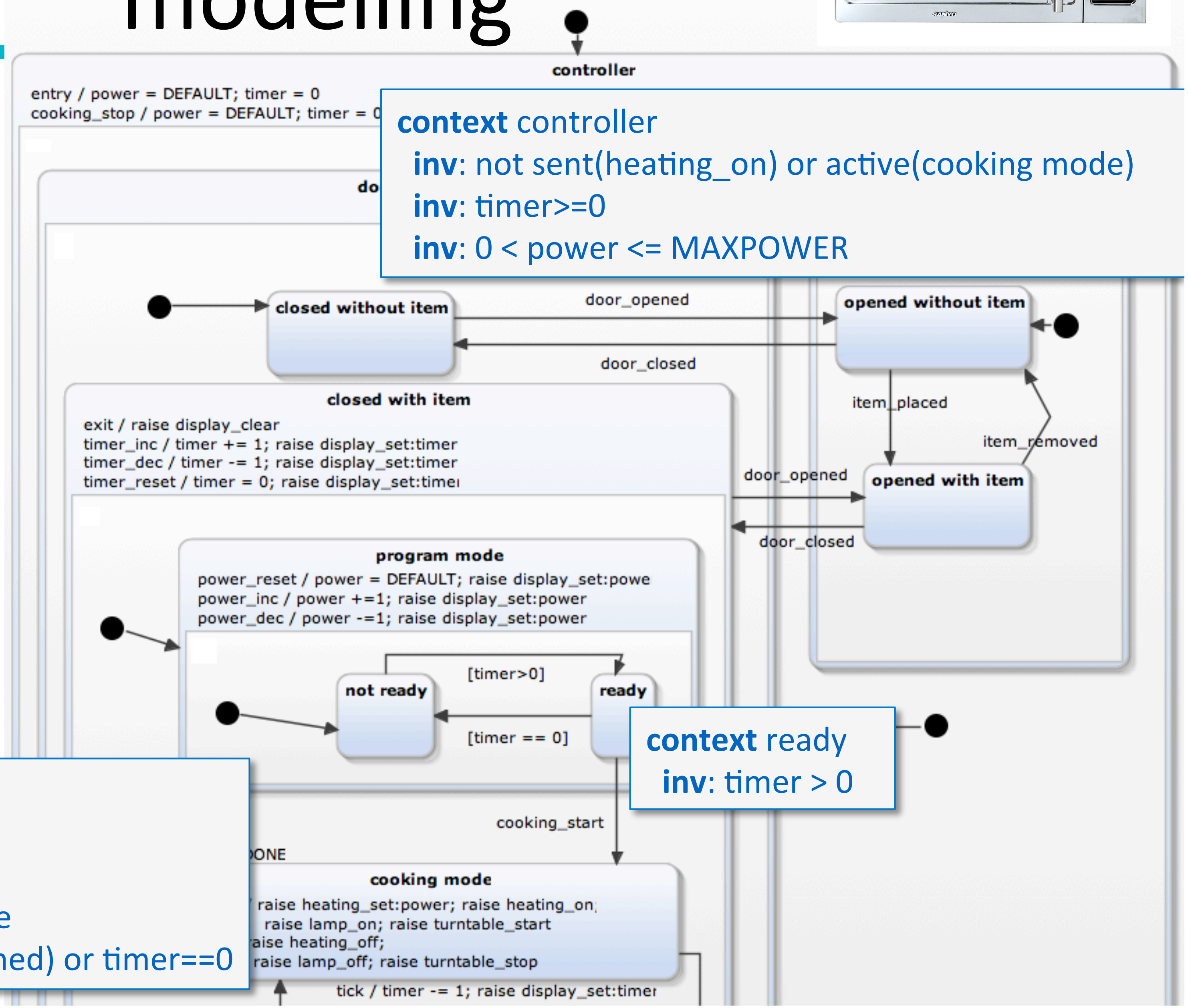
Contract-driven development

Example
(taken from www.eiffel.com/values/design-by-contract/ introduction)

```
class DICTIONARY [ ELEMENT ]
 feature
  put (x : ELEMENT; key : STRING ) is
  require
    count <= capacity
    not key.empty
  ensure
    has (x)
    item (key) = x
    count = old count + 1
 end
 invariant
   0 <= count
   count <= capacity
 end
```

Contract-driven modelling

Contracts for microwave controller



context controller
inv: not sent(heating_on) or active(cooking mode)
inv: timer>=0
inv: 0 < power <= MAXPOWER

context ready
inv: timer > 0

context cooking mode
pre: timer>0
inv: timer >= 0
inv: power == power@pre
post: received(door_opened) or timer==0

Telling stories

```
Story(
  event door_opened,
  event item_placed,
  event door_closed,
  event timer_dec
).tell(interpreter)
```

Example of failing contract

InvariantError

State: controller

Assertion: timer >= 0

Configuration:

[controller, door closed, closed with item,
program mode, not ready]

Step:

event timer_dec

internal transition on closed with item

Solution to failing contract

Add guards to the actions associated to the events that increment and decrement power and timer

timer_dec [timer>0] / timer -= 1

power_inc [power<MAXPOWER] / power += 1

power_dec [power>1] / power -= 1

Test-driven development

test negative_timer:

Story(door_opened, item_placed, door_closed, timer_dec).tell(statechart)

statechart.execute()

assertEqual(State(controller).timer, 0)

test *no_heating_when_door_is_not_closed*:

Story(door_opened, item_placed, timer_inc, cooking_start).tell(statechart)

statechart.execute()

assertFalse active(cooking mode)

assertFalse sent(heating_on)

```
test negative_timer ... FAIL
test no_heating_when_door_is_not_closed ... ok
========================================
AssertionError: -1 != 0
----------------------------------------------------------------------
Ran 2 tests in 0.005s
FAILED (failures=1)
```

Without guards on timer_dec event

Test-driven development

test negative_timer:

Story(door_opened, item_placed, door_closed, timer_dec).tell(statechart)

statechart.execute()

assertEqual(State(controller).timer, 0)

test *no_heating_when_door_is_not_closed*:

Story(door_opened, item_placed, timer_inc, cooking_start).tell(statechart)

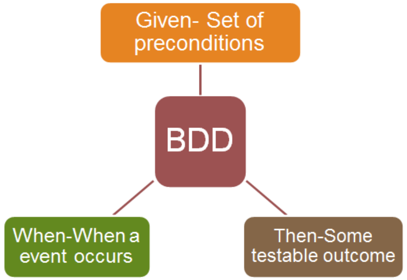
statechart.execute()

assertFalse active(cooking mode)

assertFalse sent(heating_on)

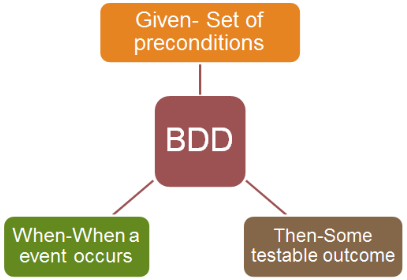
With guards on timer_dec event

```
test negative_timer ... ok
test no_heating_when_door_is_not_closed ... ok
----------------------------------------------------------------
Ran 2 tests in 0.005s
OK
```



Behaviour-Driven Development

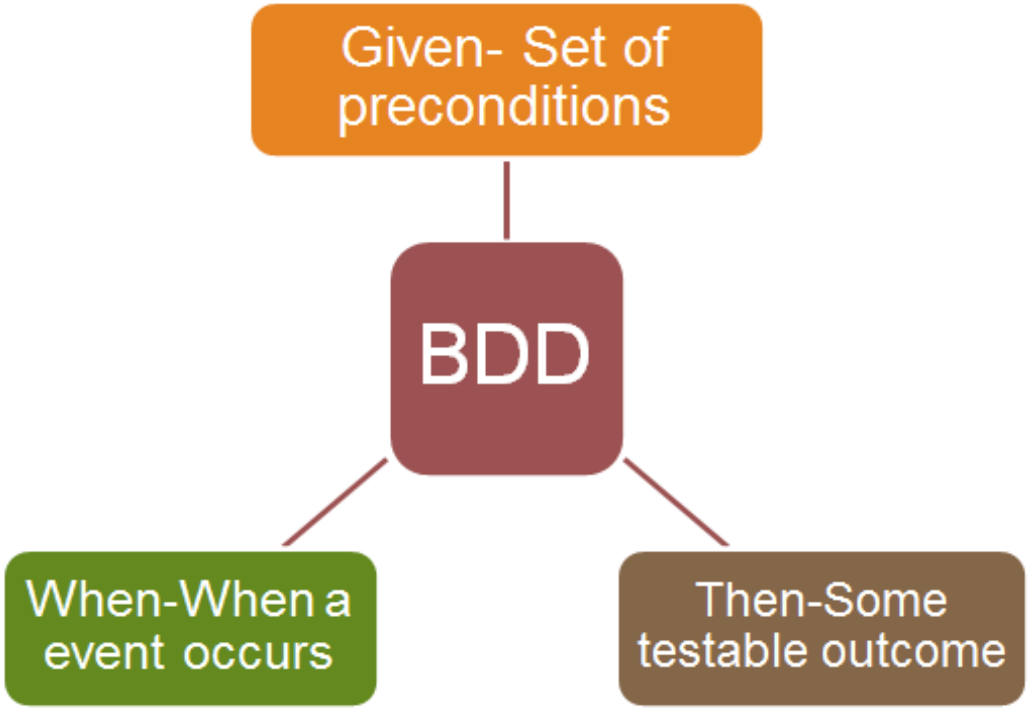
- Include customer test practices into TDD
- Encourage collaboration between developers, QA, and non- technical stakeholders (domain experts, project managers, users)
- Use a domain-specific (non-technical) language to specify how the code should behave
  - By defining feature specifications and scenarios
- Reduces the technical gap between developers and other project stakeholders

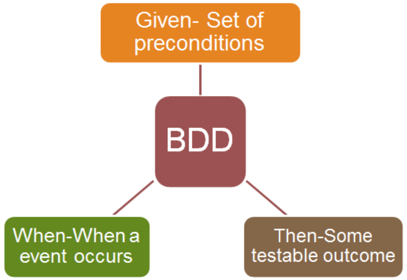


Behaviour-driven development

Software behaviour can be described in a domain-specific (non-technical) language suited to non-developers

- using the *Gherkin* language
- Supported by *Cucumber* framework in many languages



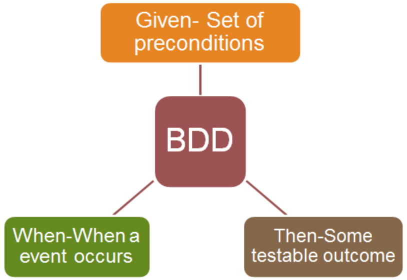


Behaviour-driven development

Example
(taken from docs.behat.org/en/v2.5/guides/1.gherkin.html)

Feature: Serve coffee
  In order to earn money customers should be able to buy coffee

  Scenario: Buy last coffee
    Given there is 1 coffee left in the machine
    And I have deposited 1 dollar
    When I press the coffee button
    Then I should be served a coffee



Behaviour-driven development

Feature: *No heating if door is opened*

Scenario: *No heating when nothing is done*

Given I do nothing

And I execute the statechart

Then state cooking_mode should not be active

And event heating_on should not be fired

Scenario: *No heating when item is placed*

Given I send event door_opened

When I send event item_placed

Then event heating_on

Scenario: *No heating wh*

Given I send event doo

And I send event item_

When I send event doo

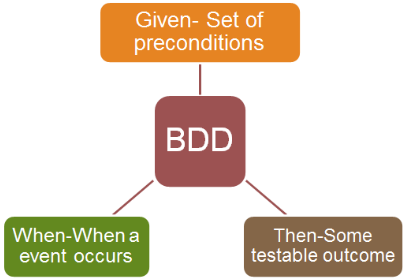
Then event heating_on

First variant.

Still refers to specific details of the statechart (state and event names)

1 feature passed, 0 failed, 0 skipped
3 scenarios passed, 0 failed, 0 skipped
11 steps passed, 0 failed, 0 skipped, 0 undefined

Took 0m0.005s



Behaviour-driven development

Feature: *No heating if door is opened*

Scenario: *No heating when nothing is done*

When I power up the microwave

Then heating should not be on

Scenario: *No heating when item is placed*

Given I open the door

When I place an item

Then heating should not turn on

Scenario: *No heating when door is not closed*

Given I open the door

And I place an item

When I close the door

Then heating should not turn on

Second variant.

Much closer to natural language. All statecharts-specific concepts are abstracted away.

Coverage analysis

State coverage: 81.82%

Entered states:

controller (3) | door closed (4) |door opened (2) |
closed without item (3) | opened without item (2) |
opened with item (2) | closed with item (1) |
not ready (1) | program mode (1)

Remaining states:

cooking mode | ready

Transition coverage: 16.67%

Processed transitions:

opened without item [item_placed] -> opened with item (2)
closed without item [door_opened] -> opened without item (2)
opened with item [door_closed] -> closed with item (1)

Property statecharts

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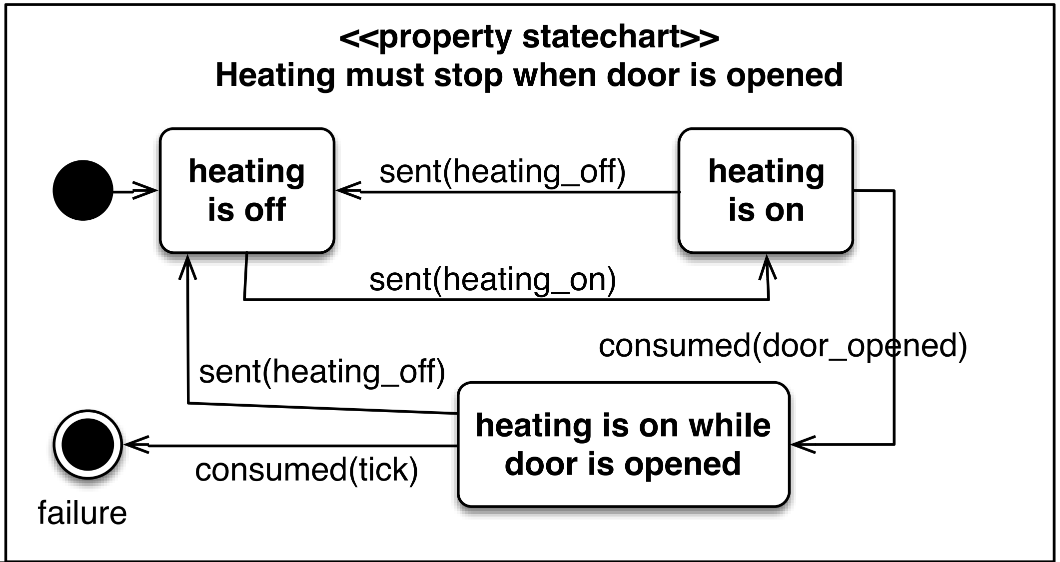
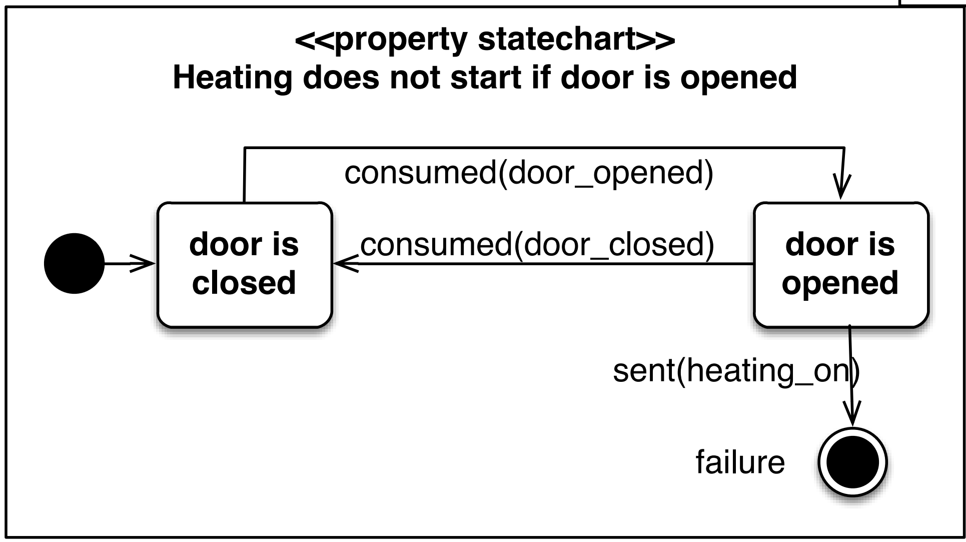
Define and verify behavioural properties by

1. instrumenting the statechart interpreter
2. intercepting specific actions of statechart being executed
   - entered(<NAME OF STATE>)
   - exited(<NAME OF STATE>)
   - consumed(<NAME OF EVENT>)
   - sent(<NAME OF EVENT>)
   - …
3. executing a *property statechart* that verifies a desirable or undesirable property

Property statecharts





Tool support

Sismic = Sismic Interactive Statechart Model Interpreter and Checker

- Python library available on Python Package Index (PyPI)
- released under open source licence LGPL v3
- Source code
  - github.com/AlexandreDecan/sismic
- Documentation
  - sismic.readthedocs.io

Tool support

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Sismic supports all aforementioned concepts

- Statechart execution
- Design by contract
- Unit testing
- BDD
- Coverage analysis
- Property statecharts
- And more…

Sismic file format

Representing a statechart as a YAML file

```
root state:
  name: controller
  contract:
    - always: not sent('heating_on') or active('cooking mode')
    - always: timer >= 0
    - always: 0 < power <= MAXPOWER
  initial: door closed
  on entry: |
    power = DEFAULT
    timer = 0
  transitions:
    - event: input_cooking_stop
      action: |
        timer = 0
```

Sismic
file format

Representing
a statechart
as a YAML file

```yaml
states:
  - name: door closed
    initial: closed without item
    states:
      - name: closed without item
        transitions:
          - event: door_opened
            target: opened without item
      - name: closed with item
        initial: program mode
        on exit: send('display_clear')
        transitions:
          - event: door_opened
            target: opened with item
          - event: input_timer_inc
            action: |
              timer = timer + 1
              send('display_set', text='TIMER: %d' % timer)
...
```

Sismic
Executing statecharts

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Stepwise execution of statechart behaviour

```
from sismic.io import import_from_yaml
from sismic.interpreter import Interpreter
from sismic.model import Event
with open('microwave.yaml') as f:
   statechart = import_from_yaml(f)
interpreter = Interpreter(statechart)
interpreter.execute_once()
       MacroStep(None, [], >['controller', 'door closed', 'closed without item'], <[])
interpreter.queue(Event('door_opened'))
interpreter.execute_once()
      MacroStep(Event(door_opened), [Transition(closed without item, opened without
      item, door_opened)], >['door opened', 'opened without item'], <['closed without
      item', 'door closed'])
```

Sismic
Running stories

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```
from sismic.stories import Story
story = Story([Event('door_opened'), Event('item_placed'), Event('door_closed'),
              Event(’timer_inc'), Event(’cooking_start'), Event(’tick')])
trace = story.tell(interpreter)
```

MacroStep(None, [], >['controller', 'door closed', 'closed without item'], <[]),

MacroStep(Event(door_opened), [Transition(closed without item, opened without item, door_opened)], >['door opened', 'opened without item'], <['closed without item', 'door closed']),

MacroStep(InternalEvent(lamp_on), [], >[], <[]),

MacroStep(Event(item_placed), [Transition(opened without item, opened with item, item_placed)], >['opened with item'], <['opened without item']),

MacroStep(Event(door_closed), [Transition(opened with item, closed with item, door_closed)], >['door closed', 'closed with item', 'program mode', 'not ready'], <['opened with item', 'door opened']),

…

Sismic
Running stories

MacroStep(InternalEvent(lamp_off), [], >[], <[]),

MacroStep(Event(timer_inc), [Transition(closed with item, None, timer_inc)], >[], <[]),

MacroStep(None, [Transition(not ready, ready, None)], >['ready'], <['not ready']),

MacroStep(InternalEvent(display_set, text=TIMER: 1), [], >[], <[]),

MacroStep(Event(cooking_start), [Transition(ready, cooking mode, cooking_start)], >['cooking mode'], <['ready', 'program mode']),

MacroStep(InternalEvent(heating_set_power, power=900), [], >[], <[]),

MacroStep(InternalEvent(heating_on), [], >[], <[]),

MacroStep(InternalEvent(lamp_on), [], >[], <[]),

MacroStep(InternalEvent(turntable_start), [], >[], <[]),

MacroStep(Event(tick), [Transition(cooking mode, None, tick)], >[], <[]),

MacroStep(None, [Transition(cooking mode, program mode, None)], >['program mode', 'not ready'], <['cooking mode']),

MacroStep(InternalEvent(display_set, text=REMAINING: 0), [], >[], <[]),

MacroStep(InternalEvent(heating_off), [], >[], <[]),

MacroStep(InternalEvent(lamp_off), [], >[], <[]), MacroStep(InternalEvent(turntable_stop), [], >[], <[]),

MacroStep(InternalEvent(beep, number=3), [], >[], <[]),

MacroStep(InternalEvent(display_set, text=DONE), [], >[], <[])]

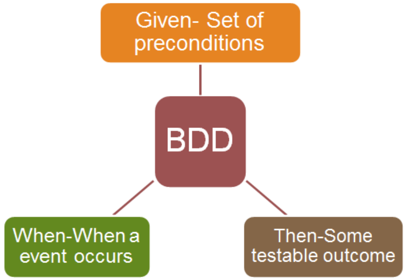
Sismic unit testing

- Using python's built-in unittest module

  $ python -m unittest heating_unittest.py –v

```
def test_no_heating_when_nothing_is_done(self):
    self.interpreter.execute()
    self.assertFalse(self.is_heating())

def test_no_heating_when_item_is_placed(self):
    events = map(Event, ['door_opened', 'item_placed'])
    story = Story(events)
    story.tell(self.interpreter)
    self.interpreter.execute()
    self.assertFalse(self.is_heating())
```



Sismic BDD

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- Using Python's behave module

  $ sismic-behave microwave.yaml --features heating.feature

```
from behave import given, when, then
from sismic.io import import_from_yaml
from sismic.interpreter import Interpreter
from sismic.interpreter.helpers import log_trace
from sismic.model import Event
@given('I execute the statechart')
def execute_statechart(context):
    _execute_statechart(context, force_execution=True)
@then('state {state_name} should be active')
def state_is_active(context, state_name):
   assert state_name in context._statechart.states, 'Unknown state {}'.format(state_name)
   assert state_name in context._interpreter.configuration, 'State {} is not active'.format(state_name)
```

Sismic
Regression testing

When an error is encountered (e.g. due to failing contract or bug), story_from_trace can reproduce the scenario of the observed behavior, which can be used as the basis of a regression test.

Sismic
Communicating statecharts

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- Statecharts can *communicate* with other statecharts or external components (e.g. a user interface) by sending/receiving events
- Realised by dynamically *binding* their statechart interpreters

Sismic
Communicating statecharts

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Example for some elevator statechart: Events sent by buttons are propagated to elevator

```
elevator = Interpreter(import_from_yaml(open('elevator.yaml')))
buttons = Interpreter(import_from_yaml(open('buttons.yaml')))
buttons.bind(elevator)
buttons.queue(Event('floor_2_pushed'))
buttons.execute()
  Awaiting events in buttons: [Event(button_2_pushed)]
  Awaiting events in buttons: [InternalEvent(floorSelected, floor=2)]
  Awaiting events in elevator: [Event(floorSelected, floor=2)]
elevator.execute()
print('Current floor:', elevator.context.get('current'))
  Current floor: 2
```

Sismic
Other features

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Other semantic variants of statecharts

- outer-first instead of inner-first semantics;
- changing priority of events
- …

Different ways of dealing with time

- Real time versus simulated time

Conclusion

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We support various ways to test statechart models

- Using contracts
- Using unit tests
- Using domain-specific features and scenarios (BDD)
- Using property statecharts

Implemented in Sismic, an open source Python library for interpreting statecharts

Future work

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- More advanced testing techniques
  - Automatic generation of contracts based on scenario specifications
  - Automatic generation of tests based on contract specifications
  - Mutation testing
  - Support for continuous integration
- Explore/compare with (dynamic?) model checking techniques
  - Based on temporal logics, labeled transition systems, …
  - Using Dwyer's specification patterns
- And many more …

Future work

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Facilitate statechart evolution

- Detecting model smells
- Model refactoring
  E.g. splitting up a complex statechart into multiple statecharts
- Semantic variation
  Detecting if statechart is compatible with alternative semantics
- Variability analysis
  Consider product families (e.g. different microwave variants) and analyse commonalities and variabilities in their statechart models
- Design space exploration
  Analyse pros and cons of syntactically different, but semantically similar statecharts