Modelling and Testing Requirements via Executable Abstract State Machines

Model-Driven Requirements Engineering (MoDRE)
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Jonathan S. Ostroff and **Chen-Wei Wang**

Case Study: An E-Health System

- *Patients* are prescribed to *medications*.
- Medications may have *dangerous interactions*.

  e.g., warfarin and aspirin both increase anti-coagulation
- Goal: *No dangerous interactions* in patients' prescriptions.

image source: `https://www.canstockphoto.ca`

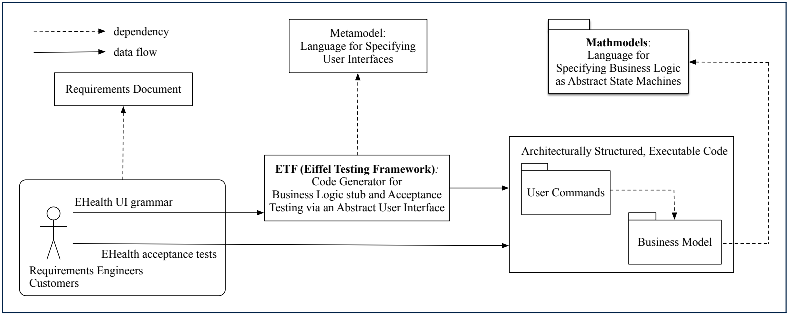
Research Problem

Given *informal* requirements describing the *problem domain*, how can we facilitate **the process** of developing *working* code in the *solution domain*?

We present a method for facilitating this process: from requirements to *formal*, *executable* specifications.

Contributions

- ***ETF*** (Eiffel Testing Framework)
  - Generates *code stub* for developing business logic
  - Supports *acceptance testing* via a given Abstract User Interface
- ***Mathmodels*** programming library
  - Specifies business logic as *abstract state machines*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Customers

- *Scalable to large systems* via *Runtime Contract Checking*.

Requirements Elicitation (1)

ENV-descriptions document environment constraints or assumptions.

ENV1	Physicians prescribe medications to *patients*.
ENV2	There exist pairs of medications that when taken together have dangerous *interactions*.
ENV3	If one *medication* interacts with another, then the reverse also applies (Symmetry).
ENV4	A medication does not interact with itself (Irreflexivity).

reflected in Mathmodels

Requirements Elicitation (2)

REQ-descriptions document what the machines must produce.

REQ5	The system shall maintain records of dangerous medication interactions.
REQ6	The system shall maintain records of patient *prescriptions*. No prescription may have a dangerous interaction.
REQ7	Physicians shall be allowed to add a medication to a patient's prescription, provided it does not result in a dangerous interaction.
REQ8	It shall be possible to add a new medication interaction to the records, provided that it does not result in a dangerous interaction.
REQ9	Physicians shall always be allowed to remove a medication from a patient's prescription.

reflected in Mathmodels

Abstract User Interface

```
system ehealth
  -- semantics types
  type MEDICATION = STRING
  type PATIENT = STRING
  -- events
  add_patient           (p: PATIENT)
  add_medication        (m: MEDICATION)
  add_interaction       (m1: MEDICATION; m2: MEDICATION)
  add_prescription      (p: PATIENT; m: MEDICATION)
  remove_interaction    (m1: MEDICATION; m2: MEDICATION)
  remove_prescription (p: PATIENT; m:MEDICATION))
```

Abstract UI may **later** be implemented using concrete desktop, mobile, or web interface.

Abstract State

Types of ***abstract*** state variables:

$$\begin{array}{lcl} \textit{patients} & \in & \mathbb{P}\,\textit{PATIENT} \\ \textit{medications} & \in & \mathbb{P}\,\textit{MEDICATION} \\ \textit{interactions} & \in & \textit{MEDICATION} \leftrightarrow \textit{MEDICATION} \\ \textit{prescriptions} & \in & \textit{PATIENT} \leftrightarrow \textit{MEDICATION} \end{array}$$

Example ***abstract state*** in ASCII form:

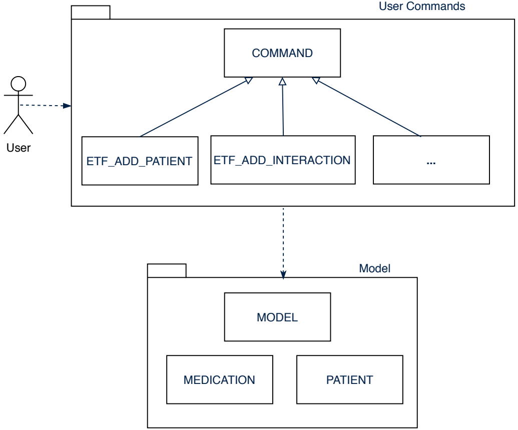
```
patients:      {p1, p2, p3}
medications:   {m1, m2, m3, m4}
interactions:  {m1 -> m2, m2 -> m1}
prescriptions: {p1 -> m1, m3; p3 -> m2,m4}
```

Acceptance Test

```
...
 state 16
 patients:      {p1,p2,p3}
 medications:   {m1,m2,m3,m4}
 interactions:  {m1->m2,m2->m1,m2->m4,m4->m2}
 prescriptions: {p1->m1,m3; p3->m2}
->add_prescription("p3","m4")
 state 17 Error e4: this prescription dangerous
->remove_interaction("m2","m4")
 state 18
 patients:      {p1,p2,p3}
 medications:   {m1,m2,m3,m4}
 interactions:  {m1->m2,m2->m1}
 prescriptions: {p1->m1,m3; p3->m2}
->add_prescription("p3","m4")
 state 19
 patients:      {p1,p2,p3}
 medications:   {m1,m2,m3,m4}
 interactions:  {m1->m2,m2->m1}
 prescriptions: {p1->m1,m3; p3->m2,m4}
```

Architecturally Structured Generated Code

- Given an *abstract UI*, ETF generates *architecturally structured code*.



- *Business logic* is specified and implemented in the `MODEL` package.
- *Error handling* is implemented in the `User Commands` package.

The Mathmodels Library

```
class
  REL[ G, H ]
inherit
  SET[ TUPLE[ G, H ] ]
feature -- immutable queries
  domain: SET[ G ]
  range: SET[ H ]
  image alias "[]" (g: G): SET[ H ]
  extended alias "+" (p: TUPLE[ G, H ]): REL[ G, H ]
  overriden_by (p: TUPLE[ G, H ]): REL[ G, H ]
feature -- mutable commands
  extend (p: TUPLE[ G, H ])
  override (p: TUPLE[ G, H ])
     ...
end
```

- *Immutable queries* for specifying *precise contracts*.
- *Mutable commands* for making *executable Abstract State Machine*.
- There are other classes in Mathmodels library: `SET`, `FUN`, `BAG`.

Mathmodels vs. Math

- Recall the *informal* R-description:

REQ6	The system maintains records of *patient prescriptions*. No prescription may have a *dangerous interaction*.

- How to *formulate* it using set theory and predicate logic?

$$\begin{aligned}&\forall p \in \mathit{patients};\ m_1, m_2 \in \mathit{medications} :\\ &\quad p \in \mathrm{dom}(\mathit{prescriptions}) \land m_1 \neq m_2 \land (m_1, m_2) \in \mathit{interactions}\\ &\qquad \Rightarrow \neg(\ (p, m_1) \in \mathit{prescriptions} \land (p, m_2) \in \mathit{prescriptions}\ )\end{aligned}$$

- How to make the above formula *executable* and *traceable*?

```
no_dangerous_interactions_REQ6 :
  across prescriptions.domain as p all
  across prescriptions[p.item] as m1 all
  across prescriptions[p.item] as m2 all
    interactions.has ( [m1.item, m2.item] )
    implies
    not( prescriptions.has( [p.item, m1.item] ) and prescriptions.has( [p.item, m2.item] ) )
  end end end
```

Using Mathmodels to Contract Abstract State

Invariants are *traceable* back to ENV- and REQ-descriptions.

```
class
  HEALTH_SYSTEM
feature -- abstract state
  patients: SET [PATIENT]
  medications: SET [MEDICATION]
  prescriptions: REL [PATIENT, MEDICATION]
  interactions: SET [INTERACTION]
invariant
  symmetry_ENV3:
    across medications as m1 all
    across medications as m2 all
      interactions.has ( [m1.item, m2.item] ) = interactions.has ( [m2.item, m1.item] )
    end end
  irreflexivity_ENV4:
    across medications as m1 all not interactions.has ( [m1.item, m1.item] ) end
  no_dangerous_interactions_REQ6:
    across prescriptions.domain as p all
    across prescriptions [p.item] as m1 all
    across prescriptions [p.item] as m2 all
      interactions.has ( [m1.item, m2.item] )
        implies not( prescriptions.has( [p.item,m1.item] ) and prescriptions.has( [p.item,m2.item] ) )
    end end end
  consistent_domain:
    prescriptions.domain ⊆ patients
end
```

Using Mathmodels to Contract Actions

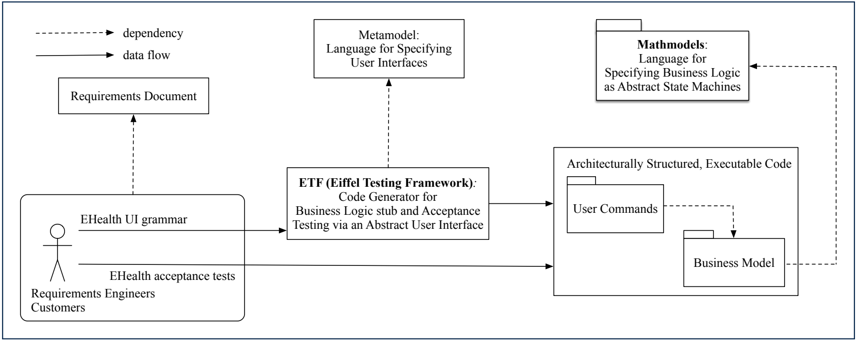
State updates are contracted with *pre-conditions* and *post-conditions*.

REQ7	Physicians shall be allowed to add a medication to a patient's prescription, provided it does not result in a dangerous interaction.

```
class
  ADD_PRESCRIPTION
inherit
  HEALTH_SYSTEM -- inherits all system invariants
feature -- commands
  add_prescription (p: PATIENT; m: MEDICATION)
        -- Add a prescription of 'm1' to 'p1'.
    require
      -- p ∈ patients
      patients.has (p)
      -- m ∉ prescriptions[p]
      not prescriptions[p].has (m)
      -- cannot cause a dangerous interaction
      -- ∀med ∈ prescriptions[p] : (med, m) ∉ interaction
      across prescriptions[p] as med all not interactions.has( [med.item, m] ) end
    do
      prescriptions.extend ([p, m])
    ensure
      prescriptions ~ old prescriptions + [p, m]
      -- UNCHANGED (patients, medications, interactions)
    end
end
```

Summary

- ***ETF*** (Eiffel Testing Framework) [code generator]
- ***Mathmodels*** programming library [specification language]



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The proposed method adopts *Design-by-Contract* (DbC) and *Eiffel programming IDE*.

⇒ *Scalable to large systems* via *Runtime Contract Checking*.

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