An Introduction to using Event-B for Cyber-Physical System Specification and Design

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SEVENTH FRAMEWORK PROGRAMME

Advance

accellera SYSTEMS INITIATIVE

2014 DESIGN AND VERIFICATION DVCON CONFERENCE AND EXHIBITION EUROPE

Outline

- ADVANCE Project Overview
- Activities supported by Rodin/Event-B Tools
- The Cyber-Physical Development Process
- The Timing Model

ADVANCE(287563)

Advanced Design and Verification Environment for Cyber-Physical System Engineering

- Cyber-Physical Systems
- Key Innovation
- Technical Approach
- Demonstration and Use

Cyber-Physical Systems

- Integrations of Computing and Physical Mechanisms
  - provide physical services
    - Transportation
    - Energy Distribution
    - Medical Care
    - Manufacturing
  - with increased
    - Adaptability
    - Autonomy
    - Efficiency
    - Safety

Cyber-Physical System Challenges

"…. the lack of temporal semantics and adequate concurrency models in computing, and today's "best effort" networking technologies make predictable and reliable real-time performance difficult, at best. "

Cyber-Physical Systems - Are Computing Foundations Adequate?

Edward A. Lee, EECS, UC Berkeley, 2006

Verifying Cyber-Physical Systems

- Most Traditional Embedded Systems are *Closed Boxes*
  - amenable to *Bench Testing*
- Cyber-Physical Systems
  - are typically networked
  - can have complex interactions with their physical environment
  - pose a much greater verification challenge
- How can predictable behaviour and timing be achieved?

Key Innovation of ADVANCE

- Focuses on the key role played by *Modelling* in Cyber-Physical System Engineering
- Modelling is used at *all* stages of the Development Process
  - From Requirements Analysis to System Acceptance Testing
- Augments Formal, Refinement-based Modelling and Verification with
  - Simulation
  - Testing

in a Single Design and Verification Environment

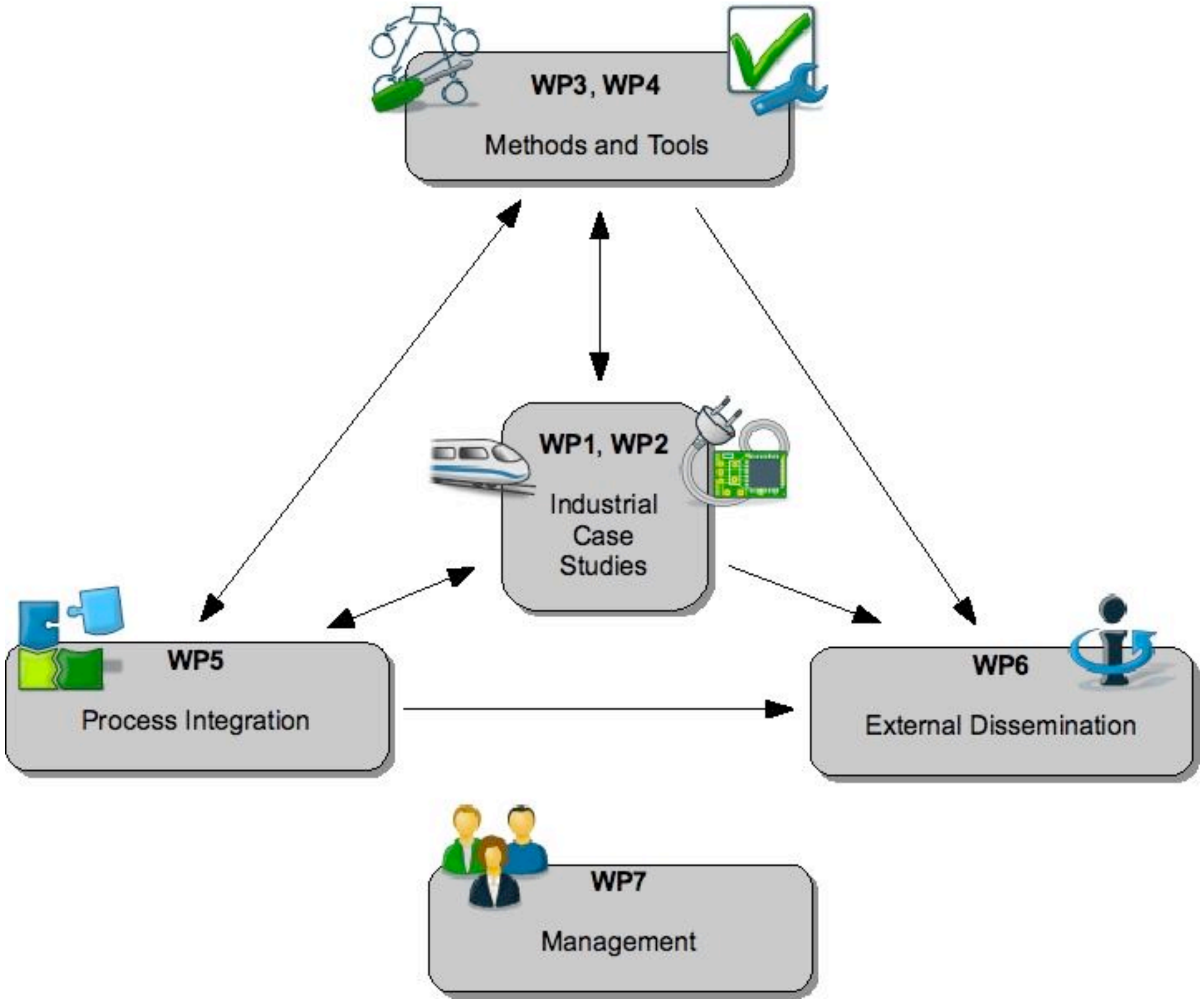
Technical Approach: Overview

- Formal Modelling supported by strong Formal Verification Tools to establish deep understanding of Specification and Design
- Simulation-based Verification to ensure that the Formal Models exhibit the expected behaviour and timing in the target physical environment
- Model-based Testing for the systematic generation of high-coverage test suites

The Multi-Simulation Framework

- Different Simulation tools are better suited to simulating different parts of a Cyber-physical system
  - Environments
  - Controllers
  - Physical Plant
- The Framework manages the co-operation of multiple simulators to enable effective Cyber-physical system verification

Demonstration and Use



ADVANCE Workpackages

WP1	Dynamic Trusted Railway Interlocking Case Study	Alstom
WP2	Smart Energy Grids Case Study	Critical
WP3	Methods and Tools for Model Construction and Proof	Systerel
WP4	Methods and Tools for Simulation and Testing	Düsseldorf
WP5	Process Integration	Southampton
WP6	External Dissemination and Exploitation	Critical
WP7	Management	Southampton

Achieving high assurance is not easy

- Requirements are poorly understood and analysed
- No software system is self-contained
  - it operates within a potentially complex environment
  - complexity of environment means that hazards / vulnerabilities in environment are poorly understood
- Designs are verified only after implementation
  - expensive to fix
  - verification usually incomplete – many undiscovered bugs
  - Ensuring coverage of faults/attacks in testing is difficult

Verified Design with Event-B

- Formal modelling at early stages to prevent errors in understanding requirements and environment
- Verify conformance between high-level specifications and designs using incremental approach
- **Rodin:** open source toolset for modelling, verification and simulation

Safety/security properties in Event-B

- Aircraft landing gear:

  $$\text{Gear=retracting} \Rightarrow \text{Door=open}$$

- Railway signalling safety:
  - The signal of a route can only be green when all blocks of that route are unoccupied

  $$\text{sig(r) = GREEN} \Rightarrow \text{blocks[r]} \cap \text{occupied} = \varnothing$$

- Access control in secure building:
  - **if** user *u* is in room *r*, **then** *u* must have sufficient authority to be in r

  $$\text{location(u) = r} \Rightarrow \text{takeplace[r]} \subseteq \text{authorised[u]}$$

Refinement in Event-B

- High level models
  - abstract details, allowing focus on system-level properties
- Refined models
  - introduce more requirements or design details
- Conformance:
  - behaviour exhibited by refined model should be allowed by abstract model
- Example, signalling mechanism as a refinement:
  - System level property:

    Gear=retracting ⇒ Door=open
  - Design level properties:

    Gear=retracting ⇒ GearRetractSignal=TRUE

    GearRetractSignal=TRUE ⇒ Door=open

Main features of the Rodin Toolset

- Model Verification
  - Ensure that Event-B models satisfy key properties formulated in a mathematical way
- Model Validation
  - Ensure that Event-B models accurately capture the intended behaviour / requirements of a system
- Model Transformation
  - Transform models from one representation to another, e.g.,
    - graphical to mathematical representation
    - model to code transformation

Simple Verification Example

Invariant: $x \leq y \leq x+C$ (y is bounded by x)

IncEvent ≙ **when** $y < x+C$ **then** $y := y+1$ **end**

- Assume the the system is initialised to a state that satisfies the invariant.
- Can the system ever get into a state in which the invariant is violated?
- Formulate the question as a mathematical problem
  - Is this theorem provable?:

$$x \leq y \leq x+C \;\wedge\; y < x+C \;\Rightarrow\; x \leq y+1 \leq x+C$$

- NB: theorem and its proof hold for all values of x,y,C.

Proof Obligations and Provers

- In Event-B theorems such as these are called Proof Obligations (POs)
  - The Rodin tool generates the POs for a model automatically
- The Rodin provers (semi-)automatically construct mathematical proofs of the validity of the POs.

Counter examples for invalid theorems

- Suppose our event had a specification error:

Invariant: $x \leq y \leq x+C$ (y is bounded by x)

IncEvent ≙ **when** y ≤ x+C **then** y := y+1 **end**

- A Model Checker can generate counterexamples that demonstrate the consequence of the error in *IncEvent* :
  - **Before:** **x=0, y=2, C=2** **ok**
  - **After:** **x=0, y=3, C=2** **fault**

- Model checker can also generate error traces from initial states:
  - **Init:** **x=0, y=0, C=2** **ok**
  - **IncEvent:** **x=0, y=1, C=2** **ok**
  - **IncEvent:** **x=0, y=2, C=2** **ok**
  - **IncEvent:** **x=0, y=3, C=2** **fault**

Model Verification in Rodin

- Proof Obligation generation
  - Invariant preservation
  - Refinement checking
- Automated and interactive proof
  - Proof manager uses a range of internal and external plug-in theorem proving tools
  - Customisable through proof tactics
- Model checking with ProB plug-in: automated search for
  - invariant violations
  - refinement violations
  - deadlocks
- Proof Support for Domain-specific theories
  - Tables and operators for data manipulation
  - Hierarchical structures (e.g. file system)
  - Train occupancy as chains on a graph

Model Validation

- Requirements tracing
  - Validating a formal model against (informal) requirements involves human judgements
  - Strong structuring and traceability helps to ensure that the validation is *comprehensive* and *maintainable*
  - Tracing is supported by ProR plug-in
- Graphical animation
  - ProB provides a simulation engine for Event-B
  - BMotionStudio allows interactive graphical animations to be constructed, driven by the simulation engine
  - Very valuable for validating model, especially with domain experts

Model Validation (continued)

- Multi-simulation
  - Event-B models discrete event systems
  - Some environment variables are best represented as continuous quantities
    - E.g., voltage, temperature, speed,…
  - Rodin multi-simulation framework allows co-simulation of discrete and continuous models
    - links ProB with external simulation tools, e.g., Simulink, Modelica
  - Co-simulation allows us to validate a discrete controller model given certain assumptions about the (continuous) environment it controls
    - environment variables represented in a continuous model

Continuous / discrete co-simulation

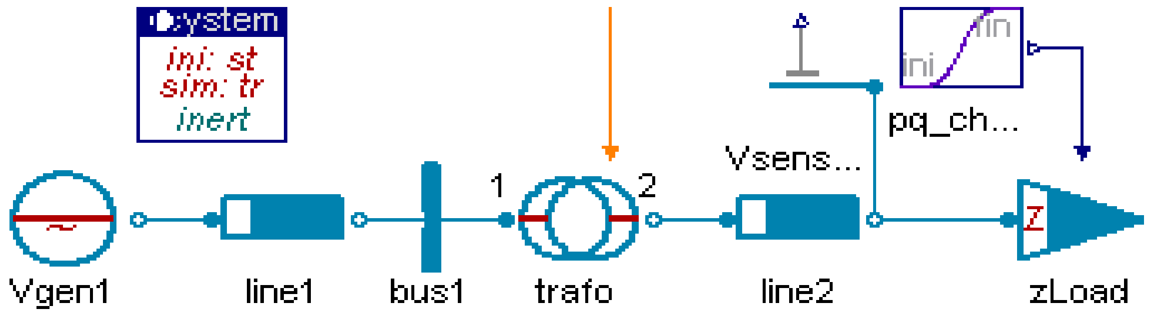


Figure 5. Distribution voltage control system in Modelica

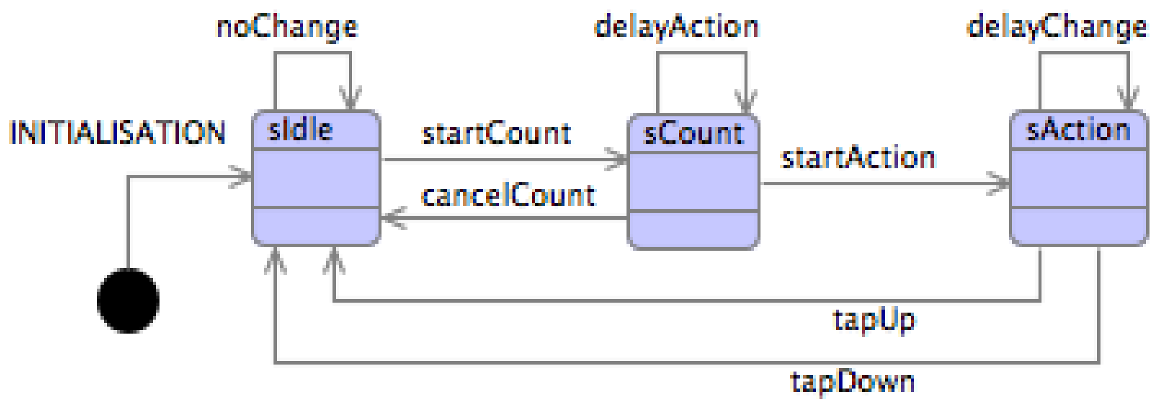


Figure 6. Event-B state machine of the OLTC controller

Co-simulation Results

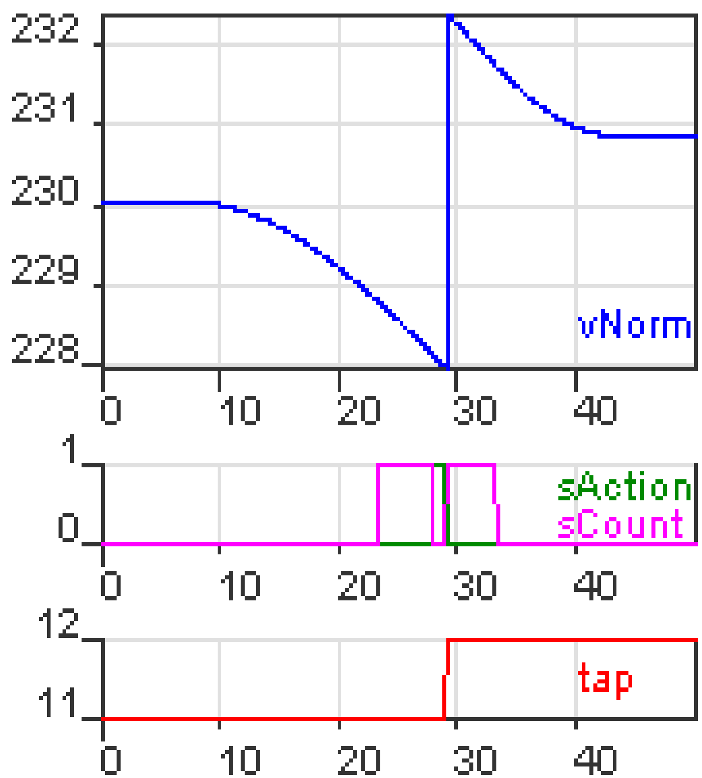


Figure 7. Co-simulation results of the OLTP voltage control (simulation time = 30s, step size = 0.1s)

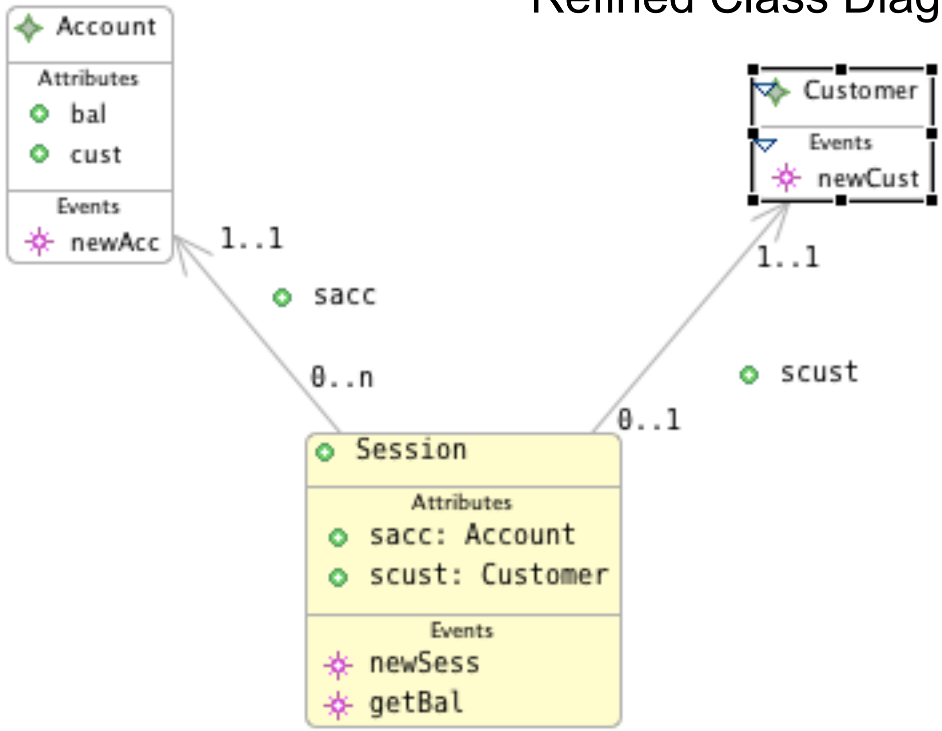
Model Transformation

- UML-B
  - UML-like graphical notation for Event-B
  - Supports class diagrams and statemachines
  - Graphical representation of refinement
- Composition and decomposition
  - Composition: combine models to form larger models
  - Decomposition: split large models into sub-models for further refinement and decomposition
  - Composition and decomposition need to be performed in a disciplined way
- Code generation
  - Generate C/Ada/Java from low-level models
  - Customisable
  - Support for generating multi-tasking implementations

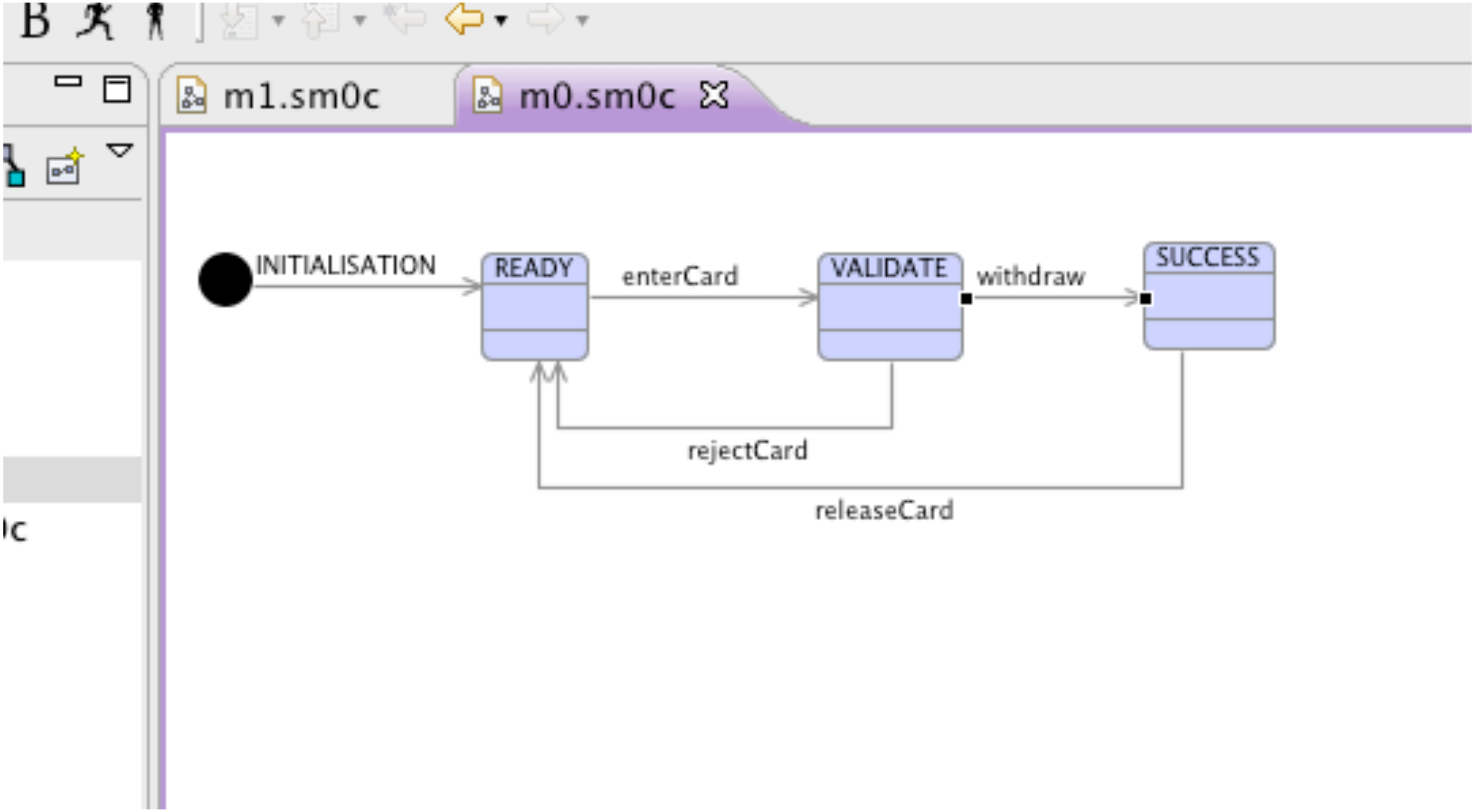
UML-B Class diagrams for Bank Accounts

Abstract Class Diagram

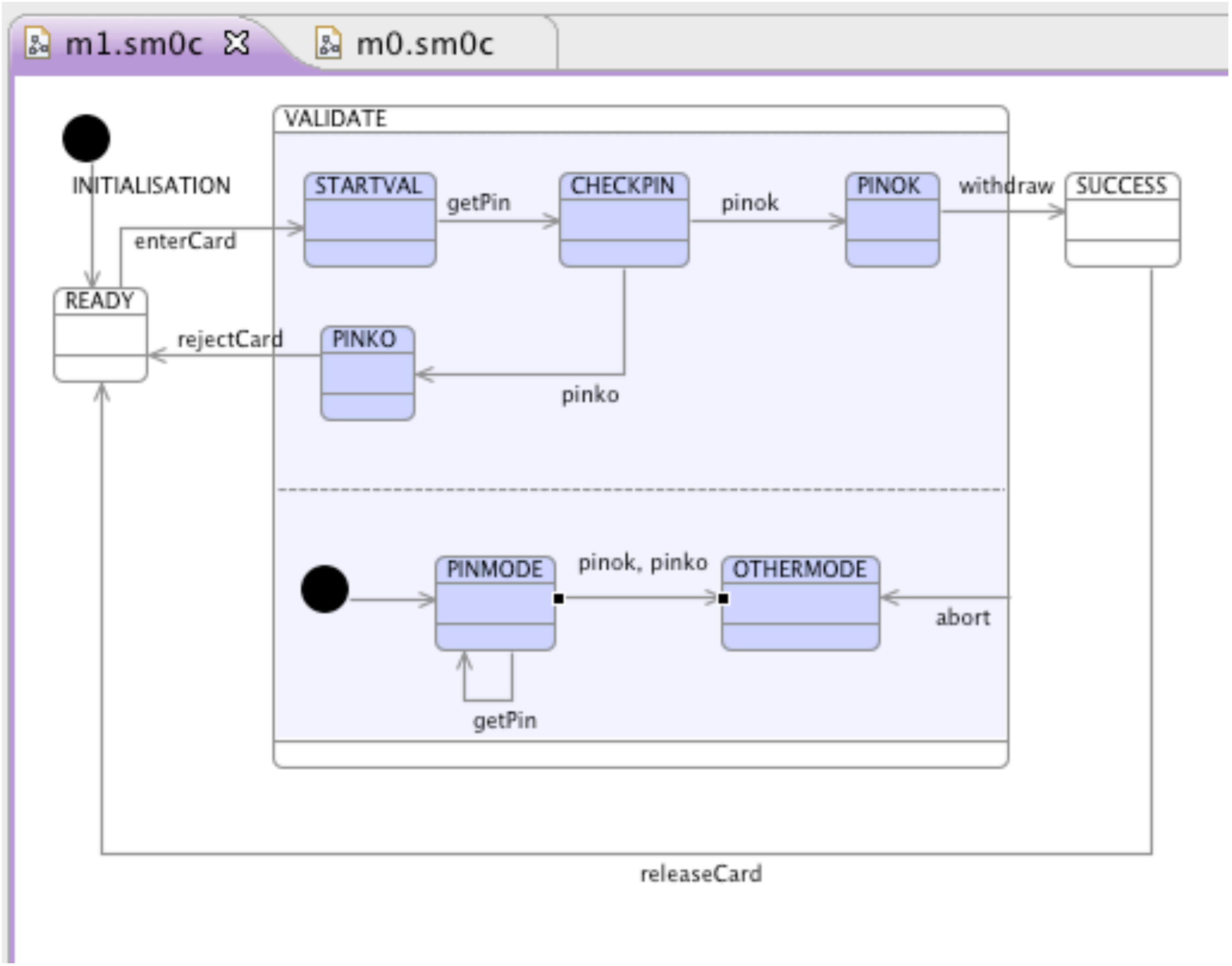
Refined Class Diagram



UML-B Statemachine for ATM



Refined model of ATM



Rodin Architecture

- Extension of Eclipse Open Source IDE
- Core Rodin Platform manages:
  - Well-formedness + type checker
  - Consistency/refinement PO generator
  - Proof manager

- Extension points to support plug-ins
  - ProB, Bmotion Studio, ProR

The ADVANCE Process

- Deriving the Safety Constraints from the Functional Requirements using STPA
- Modeling the Safety Constraints in Event-B
  - System-level Safety Constraints
- Determining how Unsafe Control Actions could occur
- Documenting the Requirements and Design Decisions with ProR
- Refining the model *and safety constraints* to ensure Control Actions are safe in the presence of Hazards
  - Architecture-level Safety Constraints
- Constraint-based test generation and MC/DC coverage
- Shared Event Decomposition
  - Further refinement/ implementation
  - FMI-based Multi-simulation

The Functional Requirements

- System Overview
- Monitored Phenomena
- *Controlled Phenomena*
- Commanded Phenomena
- Mode Phenomena

Controlled Phenomena

Landing Gear Doors

1. The Controller will *open* the Doors when the Pilot moves the Lever to Extend or Retract the Landing Gear
2. The Controller will then *close* the Doors when the Landing Gear is fully Extended or Retracted
3. The Doors will remain *open* while the Landing Gear is Extending or Retracting

Safety Requirements

“Any controller – human or automated – needs a model of the process being controlled to control it effectively”

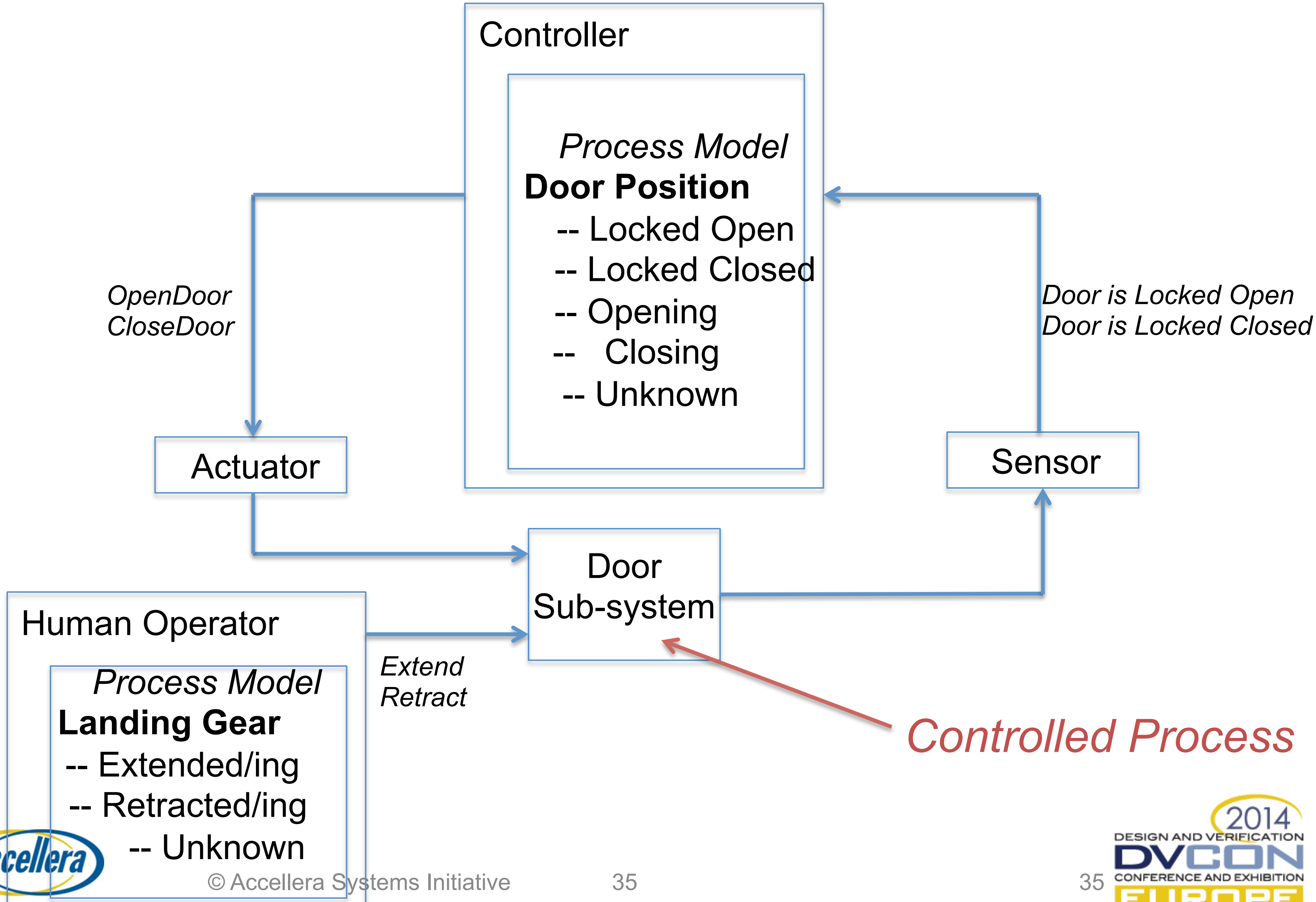
“Accidents can occur when the controller’s process model does not match the state of the system being controlled and the controller issues unsafe commands.”

Engineering a Safer World, Leveson, 2012

System-Theoretic Process Analysis (STPA)

1. Identify Potentially Hazardous Control Actions and derive the Safety Constraints
2. Determine how Unsafe Control Actions could occur

The Door Sub-system Process Models



Step I: Identify Potentially Hazardous Control Actions and Derive Safety Constraints

Controller Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing or Order Causes Hazard	Stopped too soon/Applied too long
Open Door	Cannot extend Landing Gear for landing	Not Hazardous	Not Hazardous	Damage to Landing Gear/ Not Hazardous
Close Door	Not Hazardous	Damage to Landing Gear	Damage to Landing Gear	Not Hazardous/ Not Hazardous

Safety Constraints

1. If the Landing Gear is Extending, the Door must be Locked Open
2. If the Landing Gear is Retracting, the Door must be Locked Open
3. A “Close Door” command must only be issued if the Landing Gear is Locked Up or Locked Down
4. An “Open Door” command must only be issued if the Landing Gear is Locked Up or Locked Down

Deriving the Formal Safety Constraints

- Natural Language Constraints developed systematically by the *Domain Experts*

1. If the Landing Gear is Extending, the Door must be Locked Open
2. If the Landing Gear is Retracting, the Door must be Locked Open
3. A "Close Door" command must only be issued if the Landing Gear is Locked Up or Locked Down
4. An "Open Door" command must only be issued if the Landing Gear is Locked Up or Locked Down

- Formal, Event-B Safety Constraints
  - Derived systematically from the Natural Language Descriptions
  - Linked to Requirements
    - ProR

Deriving the Formal Safety Constraints

- Natural Language Constraints developed systematically by the *Domain Experts*

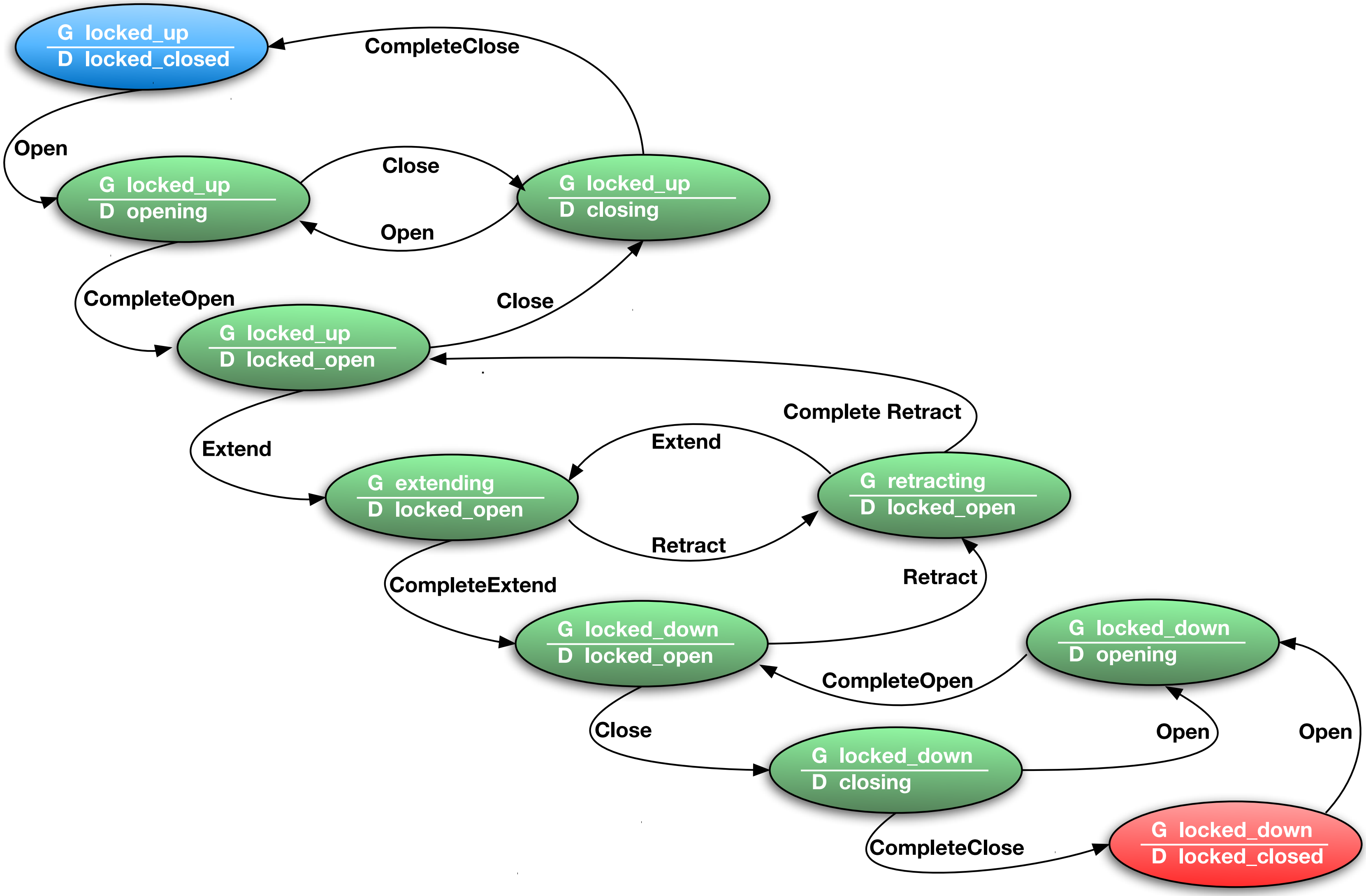
gearstate ∈ {**locked_down, locked_up**} ∨ **doorstate = locked_open**

Up or Locke

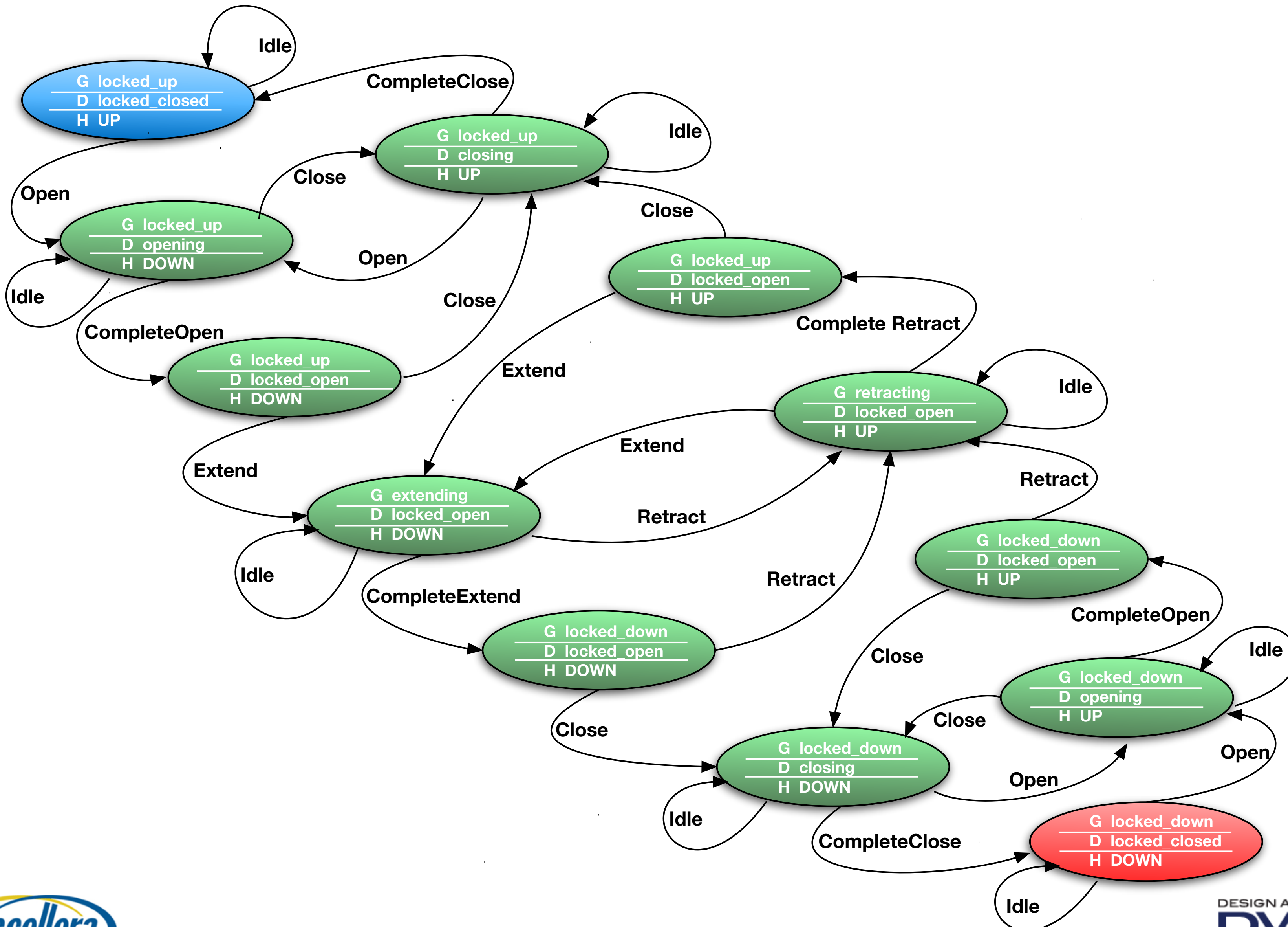
- Formal, Eve
  - Derived s … iptions
  - Linked to
    - ProR

```
event Close
  where
    @grd1 gearstate ∈ {locked_down, locked_up}
    @grd2 doorstate ∈ {opening, locked_open}
  then
    @act1 doorstate ≔ closing
end
```

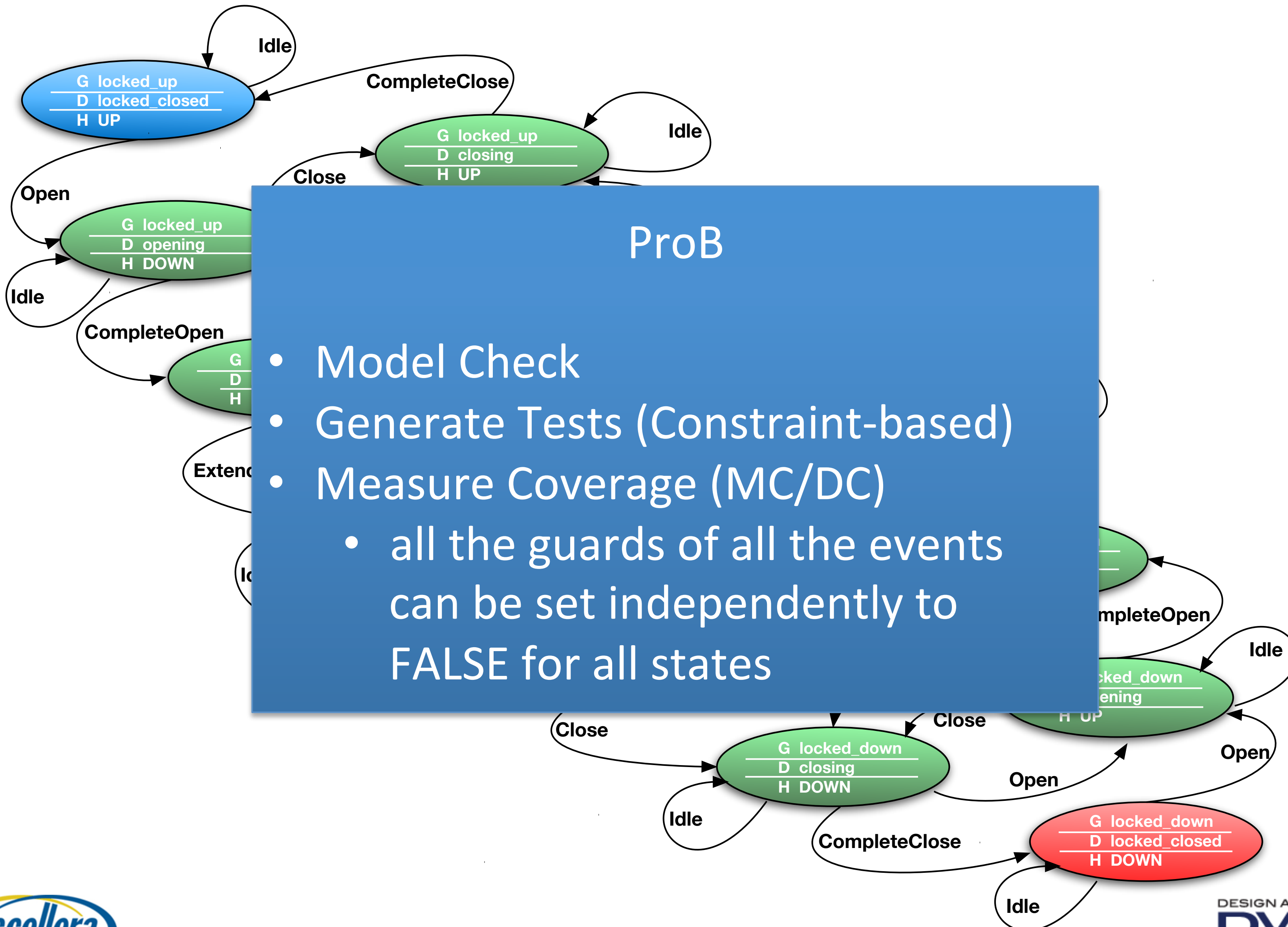
The Model Extended FSM



Refinement: Introducing the Handle and Timing



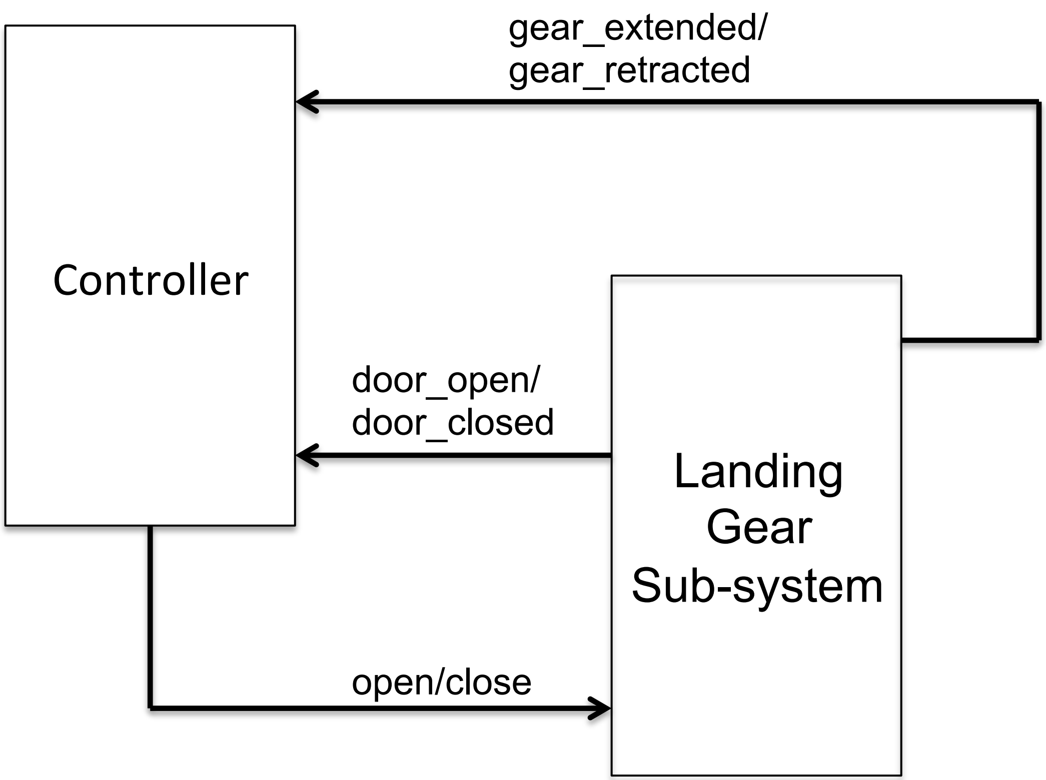
Refinement: Introducing the Handle and Timing



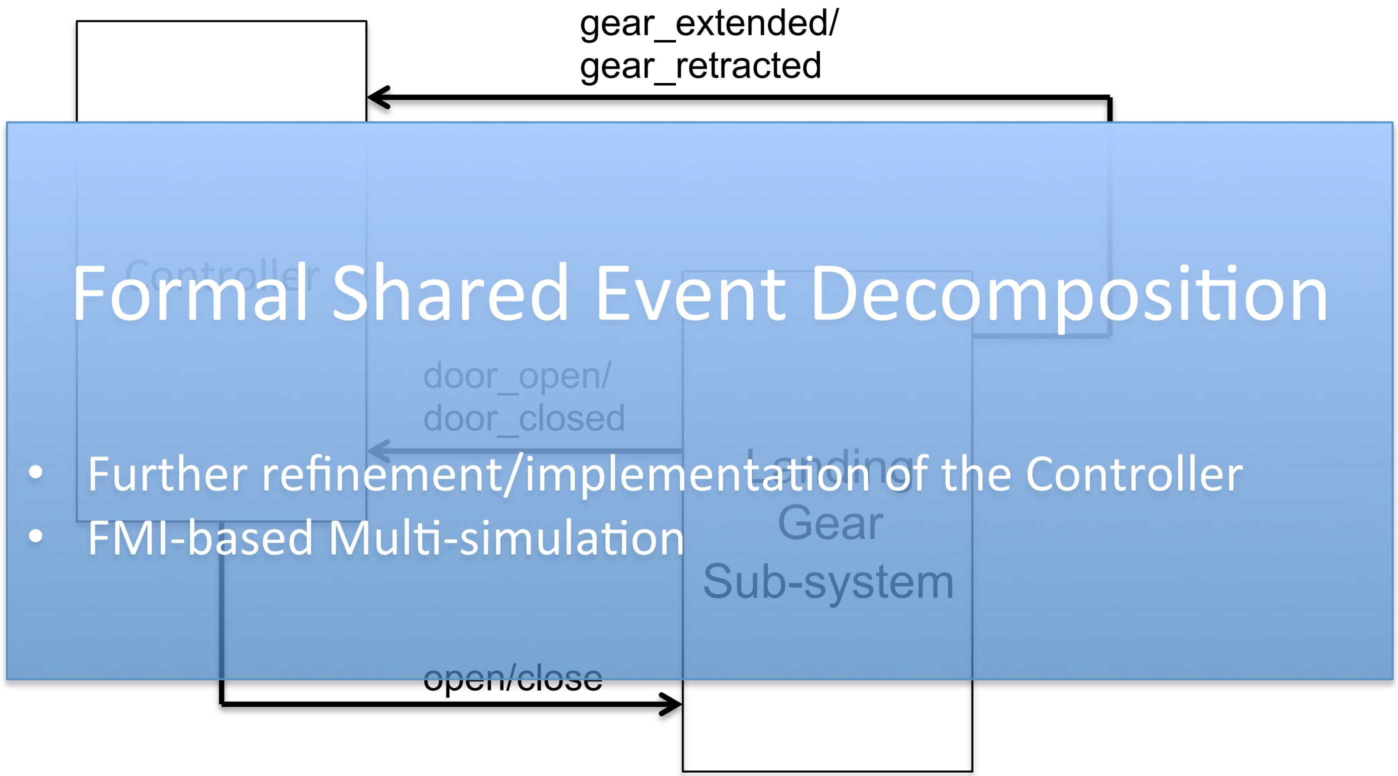
ProB

- Model Check
- Generate Tests (Constraint-based)
- Measure Coverage (MC/DC)
  - all the guards of all the events can be set independently to FALSE for all states

Refinement: The Component View Architecture-Level



Refinement: The Component View
Architecture-Level



Formal Shared Event Decomposition

- Further refinement/implementation of the Controller
- FMI-based Multi-simulation

Why Model Timing?

A major challenge that CPS present to systems modelling is that a well-developed notion of time needs to be introduced ..
[Lee and Seshia, Introduction to Embedded Systems A Cyber-Physical Approach 2011]

.. and often this is necessary quite early in the model refinement process.
We want to reason formally about the temporal properties of a Cyber-Physical System.

Why Synchronous?

- Critical timing paths can be identified through formal static timing analysis
  - *Prove* that the clock period is sufficiently long
- Proven synthesis route to a hardware implementation
- Enables interrupt-free software implementations
  - Easier to verify for safety-critical implementation

Milner's Synchronous Calculus of Communicating Systems (SCCS)

- $P \xrightarrow{a} P'$
  - An agent *P* may perform an atomic action *a* and become *P'* in doing so.
- Assuming time is discrete
  - *P* at time *t* becomes *P'* at time *t + 1*
  - Actions are atomic in the sense that they are indivisible *in time* (but not indivisible in every sense)
- A system of 3 agents *P, Q* and *R* where

  $$P \xrightarrow{a} P', \quad Q \xrightarrow{b} Q', \quad R \xrightarrow{c} R'$$

  can perform the product (*X*) of *a*, *b* and *c simultaneously* and *X* is *associative* and *commutative*
- An agent that cannot perform an action must at least be able to perform an *idle* action *i*
  - Otherwise *"disaster"*

Calculi for Synchrony and Asynchrony, 1982

Abstract Untimed Specification

```
event  EstablishCommsLink
   where
     @grd1 ControllerActive = FALSE
   then
     @act1 ControllerActive ≔ TRUE
end
```

Not an Atomic process, so

```
event  InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
  then
    @act1 TCInit ≔ TRUE
 end

 event CompleteCommsLink  refines EstablishCommsLink
  any pack
  where
    @grd1 pack = TRUE
    @grd2 TCInit = TRUE
    @grd3 ControllerActive = FALSE
  then
    @act1 ControllerActive ≔ TRUE
 end
```

AND THEN …

Handle Soft and Hard Errors

```
event  InitiateCommsLink
  where
   @grd1 ControllerActive = FALSE
   @grd2 TCInit = FALSE
  then
   @act1 TCInit ≔ TRUE
 end
```

```
event CompleteCommsLink  refines
                    EstablishCommsLink
 any pack
  where
   @grd1 pack = TRUE
   @grd2 TCInit = TRUE
   @grd3 ControllerActive = FALSE
  then
   @act1 ControllerActive ≔ TRUE
 end
```

```
event RetryCommsLink
  any pack
  where
   @grd1 pack = FALSE
   @grd2 TCInit = TRUE
   @grd3 ControllerActive = FALSE
   @grd4 RetryCount  >  0
  then
   @act1 RetryCount  ≔  RetryCount - 1
 end
```

```
event CompleteCommsLinkFail
  any pack
  where
   @grd1 pack = FALSE
   @grd2 TCInit = TRUE
   @grd3 ControllerActive = FALSE
   @grd4 RetryCount  =  0
  then
   @act1 TCInit  ≔  FALSE
 end
```

Are we Done?

- $P \xrightarrow{a} P'$
  - We have a set of four atomic actions *a*
  - At least one event in the system is always enabled
  - Under the interpretation *"the evaluation of an event advances discrete time"* we have implemented SCCS
- *BUT*
  - This is a very simple system
  - For complex CPS it is not usually feasible to represent the action as a single event
  - Recall "Actions are atomic in the sense that they are indivisible *in time* (but not indivisible in every sense)"
  - and we have only considered a single process ....

Implementing SCCS with Actions comprising multiple events

- After the system initiates the comms link it WAITs for a response
- If there is no response, it retrys and WAITs again
- So, we implement an action as a sequence of events:-
  - Evaluate, E1, E2, … Wait

Multi-event action: $C \longrightarrow C'$

```
event CEvaluate
  where
    @grd1 CEvaluated = FALSE
    @grd2 Cstep = 0
  then
    @act1 Cstep ≔ 1
 end

event CWait
  where
    @grd1 Cstep = 2
  then
    @act1 Cstep ≔ 0
    @act2 CEvaluated ≔ TRUE
 end
```

```
event  InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
    @grd3 Cstep = 1
  then
    @act1 TCInit ≔ TRUE
    @act2 Cstep ≔ 2
end
 ..
event CompleteCommsLink  refines
                                EstablishCommsLink
 any pack
  where
    @grd1 pack = TRUE
    @grd2 TCInit = TRUE
    @grd3 ControllerActive = FALSE
    @grd4 Cstep = 1
  then
    @act1 ControllerActive ≔ TRUE
    @act2 Cstep ≔ 2
 end
```

Update Event advances Time

```
event CEvaluate
  where
    @grd1 CEvaluated = FALSE
    @grd2 Cstep = 0
  then
    @act1 Cstep ≔ 1
  end

event CWait
  where
    @grd1 Cstep = 2
  then
    @act1 Cstep ≔ 0
    @act2 CEvaluated ≔ TRUE
  end

event Update
  where
    @grd1 CEvaluated = TRUE
  then
    @act1 CEvaluated ≔ FALSE
  end
```

```
event  InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
    @grd3 Cstep = 1
  then
    @act1 TCInit ≔ TRUE
    @act2 Cstep ≔ 2
end
..
event CompleteCommsLink  refines
                              EstablishCommsLink
  any pack
  where
    @grd1 pack = TRUE
    @grd2 TCInit = TRUE
    @grd3 ControllerActive = FALSE
    @grd4 Cstep = 1
  then
    @act1 ControllerActive ≔ TRUE
    @act2 Cstep ≔ 2
  end
```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2 processes: $C \longrightarrow C', T \longrightarrow T'$

```
event CEvaluate
  where
    @grd1 CEvaluated = FALSE
    @grd2 Cstep = 0
  then
    @act1 Cstep ≔ 1
 end
 ...
event CWait
  where
    @grd1 Cstep = 2
  then
    @act1 Cstep ≔ 0
    @act2 CEvaluated ≔ TRUE
 end
```

```
Event TEvaluate
  where
    @grd1 TEvaluated = FALSE
    @grd2 Tstep = 0
  then
    @act1 Tstep ≔ 1
 end
 ...
Event TWait
  where
    @grd1 Tstep = 3
  then
    @act1 Tstep ≔ 0
    @act2 TEvaluated ≔ TRUE
 end
```

```
event Update
  where
    @grd1 CEvaluated = TRUE
    @grd2 TEvaluated = TRUE
  then
    @act1 CEvaluated ≔ FALSE
    @act2 TEvaluated ≔ FALSE
 end
```

Inter-process Communication

```
event InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
    @grd3 Cstep = 1
  then
    @act1 TCInit ≔ TRUE
    @act2 Cstep ≔ 2
end
..
event CompleteCommsLink refines
                        EstablishCommsLink
 any pack
  where
    @grd1 pack = TCAcknowledgeInit
    @grd2 TCInit = TRUE
    @grd3 TCAcknowledgeInit = TRUE
    @grd4 ControllerActive = FALSE
    @grd5 Cstep = 1
  then
    @act1 ControllerActive ≔ TRUE
    @act2 Cstep ≔ 2
 end
```

```
event TAcknowledgeInit
 any pack
  where
    @grd1 pack ∈ BOOL
    @grd2 TCInit = TRUE
    @grd3 Tstep = 1
  then
    @act1 TCAcknowledgeInit ≔ pack
    @act2 Tstep ≔ 2
 end
..
```

```
event Update
  where
    @grd1 CEvaluated = TRUE
    @grd2 TEvaluated = TRUE
  then
    @act1 CEvaluated ≔ FALSE
    @act2 TEvaluated ≔ FALSE
 end
```

Inter-process Communication

```
event InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
    @grd3 Cstep = 1
  then
    @act1 TCInit ≔ TRUE
    @act2 Cstep ≔ 2
end
..
even
 any
  wh
    @
    @
    @
    @grd4 ControllerActive = FALSE
    @grd5 Cstep = 1
  then
    @act1 ControllerActive ≔ TRUE
    @act2 Cstep ≔ 2
 end
```

```
event TAcknowledgeInit
 any pack
  where
    @grd1 pack ∈ BOOL
    @grd2 TCInit = TRUE
    @grd3 Tstep = 1
  then
    @act1 TCAcknowledgeInit ≔ pack
    @act2 Tstep ≔ 2
 end
```

Evaluation of C and T is order dependent!
Does not preserve *commutativity* required by SCCS
Race Condition

```
  then
    @act1 CEvaluated ≔ FALSE
    @act2 TEvaluated ≔ FALSE
 end
```

Preserving evaluation order independence

```
event InitiateCommsLink
  where
    @grd1 ControllerActive = FALSE
    @grd2 TCInit = FALSE
    @grd3 Cstep = 1
  then
    @act1 TCInitprime ≔ TRUE
    @act2 Cstep ≔ 2
end
..
event CompleteCommsLink refines
                         EstablishCommsLink
 any pack
  where
    @grd1 pack = TCAcknowledgeInit
    @grd2 TCInit = TRUE
    @grd3 TCAcknowledgeInit = TRUE
    @grd4 ControllerActive = FALSE
    @grd5 Cstep = 1
  then
    @act1 ControllerActive ≔ TRUE
    @act2 Cstep ≔ 2
 end
```

```
event TAcknowledgeInit
 any pack
  where
    @grd1 pack ∈ BOOL
    @grd2 TCInit = TRUE
    @grd3 Tstep = 1
  then
    @act1 TCAcknowledgeInitprime ≔ pack
    @act2 Tstep ≔ 2
 end
..
```

```
event Update
  where
    @grd1 CEvaluated = TRUE
    @grd2 TEvaluated = TRUE
  then
    @act1 CEvaluated ≔ FALSE
    @act2 TEvaluated ≔ FALSE
    @act3 TCInit ≔ TCInitprime
    @act4 TCAcknowledgeInit ≔
            TCAcknowledgeInitprime
 end
```

Preserving evaluation order independence

event InitiateCommsLink
where
@grd1 ControllerActive = FALSE
@grd2 TCInit = FALSE
@grd3 C
then
@act1 T(
@act2 C
end
..
event Comp

event TAcknowledgeInit
any *pack*
where
@grd1 *pack* ∈ *BOOL*

Update event
updates the values of the communication variables
and advances time when all processes have evaluated

EstablishCommsLink
any *pack*
where
@grd1 *pack* = ***TCAcknowledgeInit***
@grd2 TCInit = TRUE
@grd3 ***TCAcknowledgeInit*** = TRUE
@grd4 ControllerActive = FALSE
@grd5 Cstep = 1
then
@act1 ControllerActive ≔ TRUE
@act2 Cstep ≔ 2
end

event Update
where
@grd1 CEvaluated = TRUE
@grd2 TEvaluated = TRUE
then
@act1 CEvaluated ≔ FALSE
@act2 TEvaluated ≔ FALSE
@act3 TCInit ≔ TCInitprime
@act4 TCAcknowledgeInit ≔
TCAcknowledgeInitprime
end

Timing Summary

- Specification refinement begins with an untimed model
- Refinement introduces sequences of temporal events
- Implementing SCCS semantics in the refined Event-B model enables synchronisation and communication between processes without race
  - Implements HDL cycle-based semantics
  - Enables HDL and Assertion generation from Event-B

Important Messages

- System assurance can be strengthened
  - using systematic processes and verified design
- Role of systematic requirements and safety analysis
  - Structures to focus the analysis
  - Path to formalisation
- Role of formal modelling and refinement:
  - increase understanding, decrease errors
  - manage complexity through multiple levels of abstraction
- Role of verification and tools:
  - improve quality of models (validation + verification)
  - make verification as automatic as possible, pin-pointing errors and even *suggesting* improvements

Questions