QoS Modelling and Verification with UML Statecharts

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The StoCharts Approach

joint work with

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Overview

- Introduction to QoS modeling and analysis
- Introduction to Statecharts
- StoCharts
  - Introduction
  - Semantics
  - Applications
- Conclusions and future outlook

Quality of Service?

- Some first remarks on QoS.

- Let's take one
  of the classical
  OO examples.

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The good old Hotel reservation system.

How about QoS here?

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How about QoS here?

Quality vs. Quantity of Service

- UML is suggested as *the* method to design systems.
- How about its support for 'model driven' QoS?

Quality vs. Quantity of Service

- UML is suggested as *the* method to design systems.
- How about its support for 'model driven' QoS?

- What's the point?
- Any QoS property we can think of comes with a *metric*, or at least, a *scale*.

Or: one needs *quantative* models to assess quality.

What QoS properties do we think of?

- Specific properties (but pretty vague still)

Image Quality
Design
Features
Performance

- Abstract properties
  - Time-related
    - Date/time, time delay, latency, etc
  - Dependability-related
    - Failure rates, message losses, availability, etc
  - Capacity-related
    - Throughput, processor load, power consumption, etc
  - Security-related characteristics
    - Protection, access control, authentication, confidentiality, etc
  - and so on ...

A brief guide through QoS Modelling

QoS models are *stochastic in nature*
to model (or abstract from)

- message buffering,
- interdependencies due to media sharing,
- communication characteristics,
- component/link failures,
- hardware circuit inaccuracies
- etc.

Markov chains,
semi-Markov processes,
Markov decision processes

- What we have out there
  - queueing networks,
  - Petri net extensions,
  - hierarchical formalisms,
  - Compositional formalisms (process algebra),
  - Annotated design methods (SDL, …, UML-Statecharts).

Stochastic models

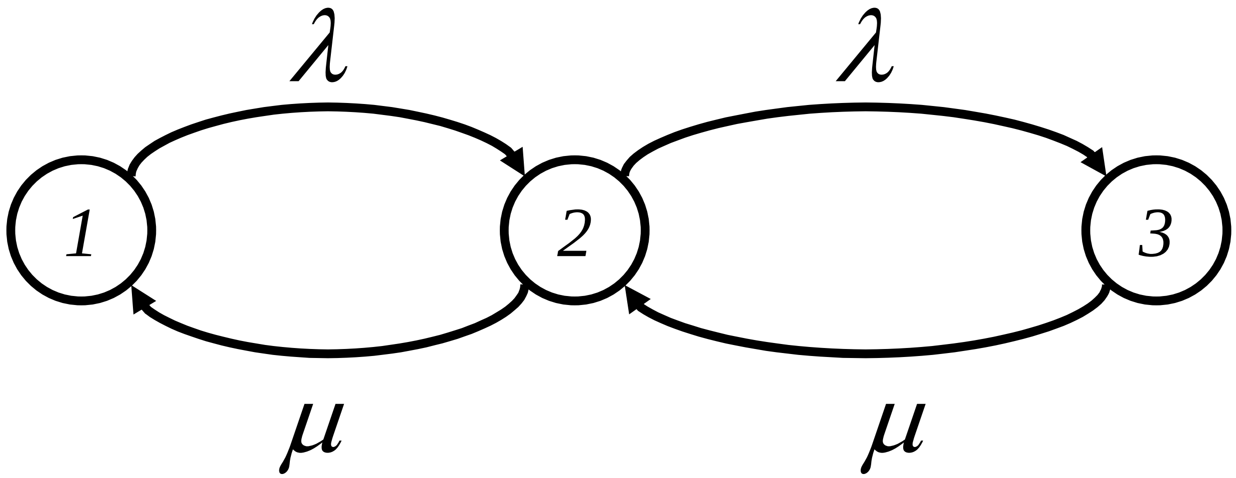
What I will tell you about (very briefly)

- their ingredients
- their analysis
- their construction

Stochastic models

Their ingredients?

- states
- transitions



- labels
  - of states
  - of transitions

States and transitions

- stochastic models describe an abstract view of a *real* system
- *states* are abstract views of system configurations
- *transitions* describe changes from one system configuration to another *as time progresses*
- *labels* represent relevant information
- Precise semantics of transition labels induces a precise description of stochastic behaviour. (Prerequisite for faithful analysis!)

A snackbar in Eindhoven

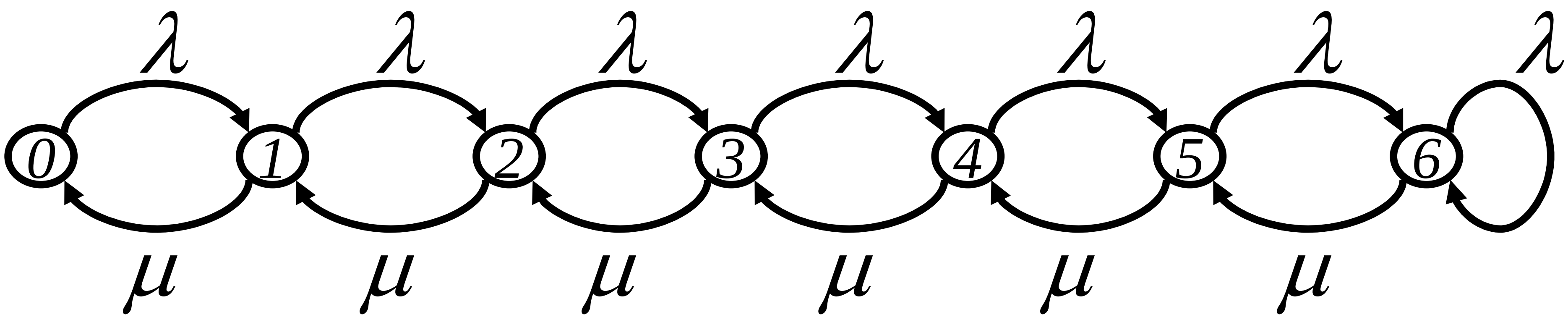
- Customers arrive at a certain frequency, say approximately 1 customer per five minutes.

  arrival rate λ = 1/5 min

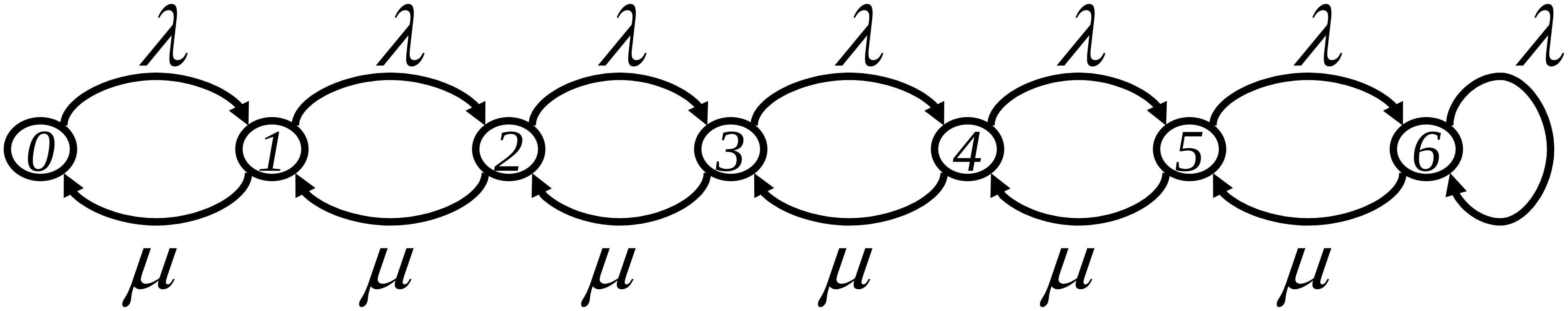
- Service requires, say, three minutes.

  service rate μ = 1/3 min

- At most six customers can wait inside the snackbar.



States and transitions

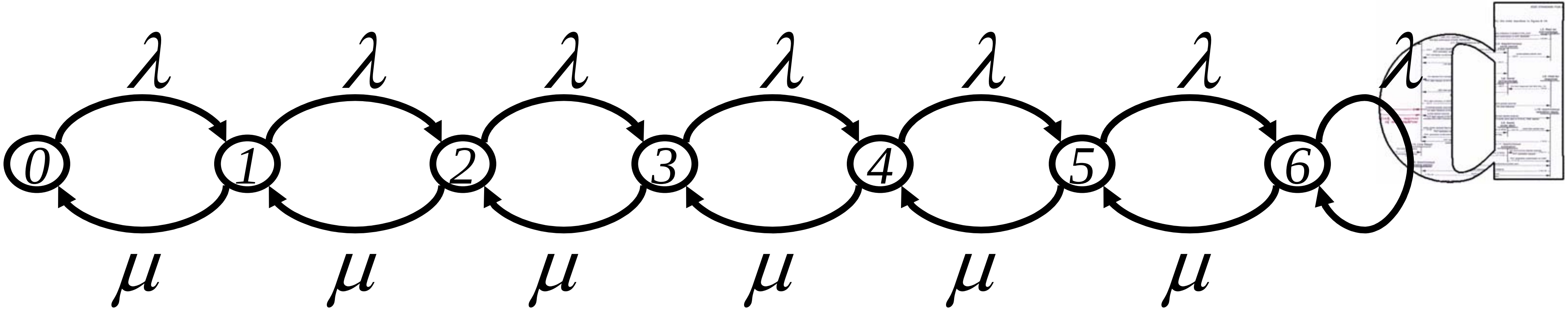


- *states* are abstract views of system configurations

here: number of customers in the snackbar

- *transitions* describe changes from one system configuration to another *as time progresses*

here: arrival and service of customers



What is this?

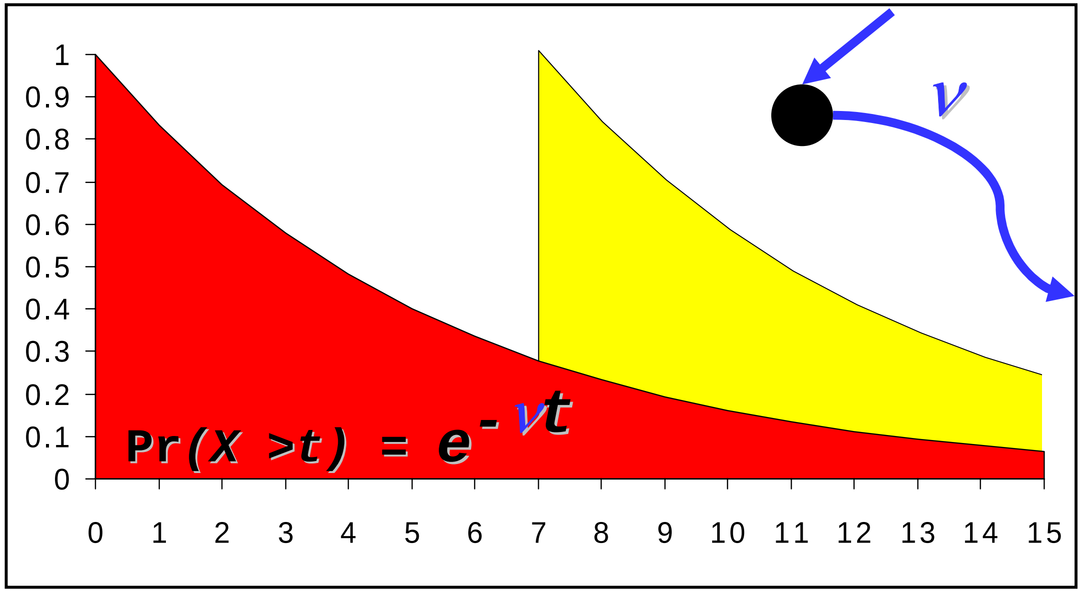
- a *stochastic process*

- more precise:
  a *Markov chain* (named after A.A. Markov, 1909)

- again more precise:
  a finite homogeneous continuous-time Markov chain

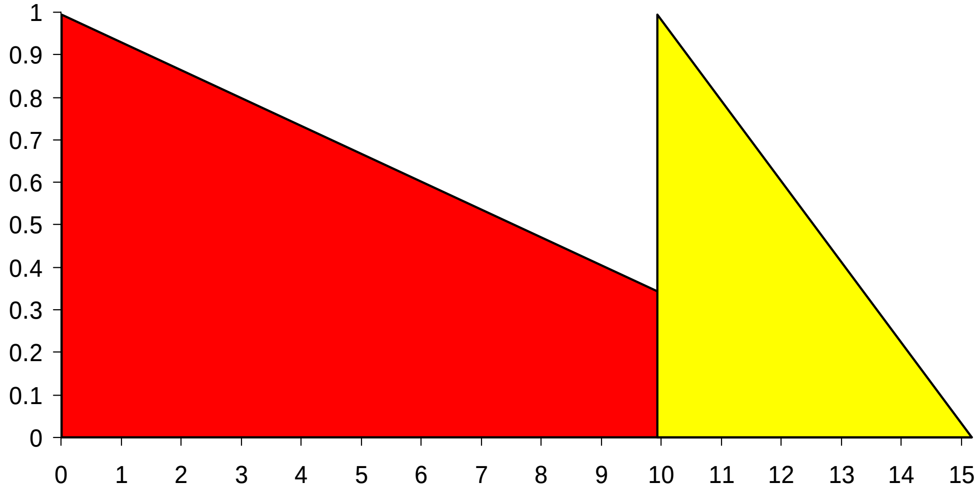
Continuous-time Markov chains

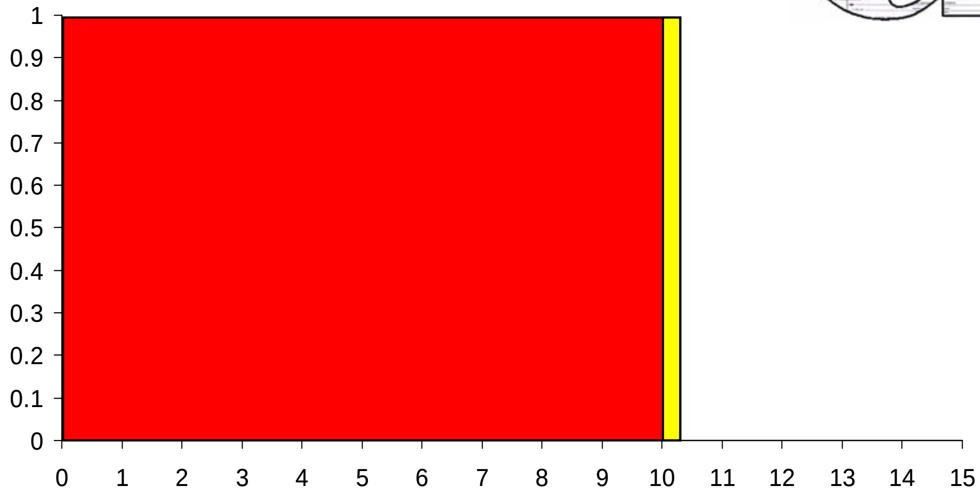
- (finite state) automata,
- all times are *exponentially distributed,*



- sojourn time in states are *memory-less,*
- very well investigated class of stochastic processes,
- widely used in practice,
- best guess, if only mean values are known,
- *efficient* and numerically *stable* algorithms for *stationary* and *transient* analysis are available.

Continuous time, *but* memory





- and many, many others

- actually:

  absence of memory is rare;

- but :

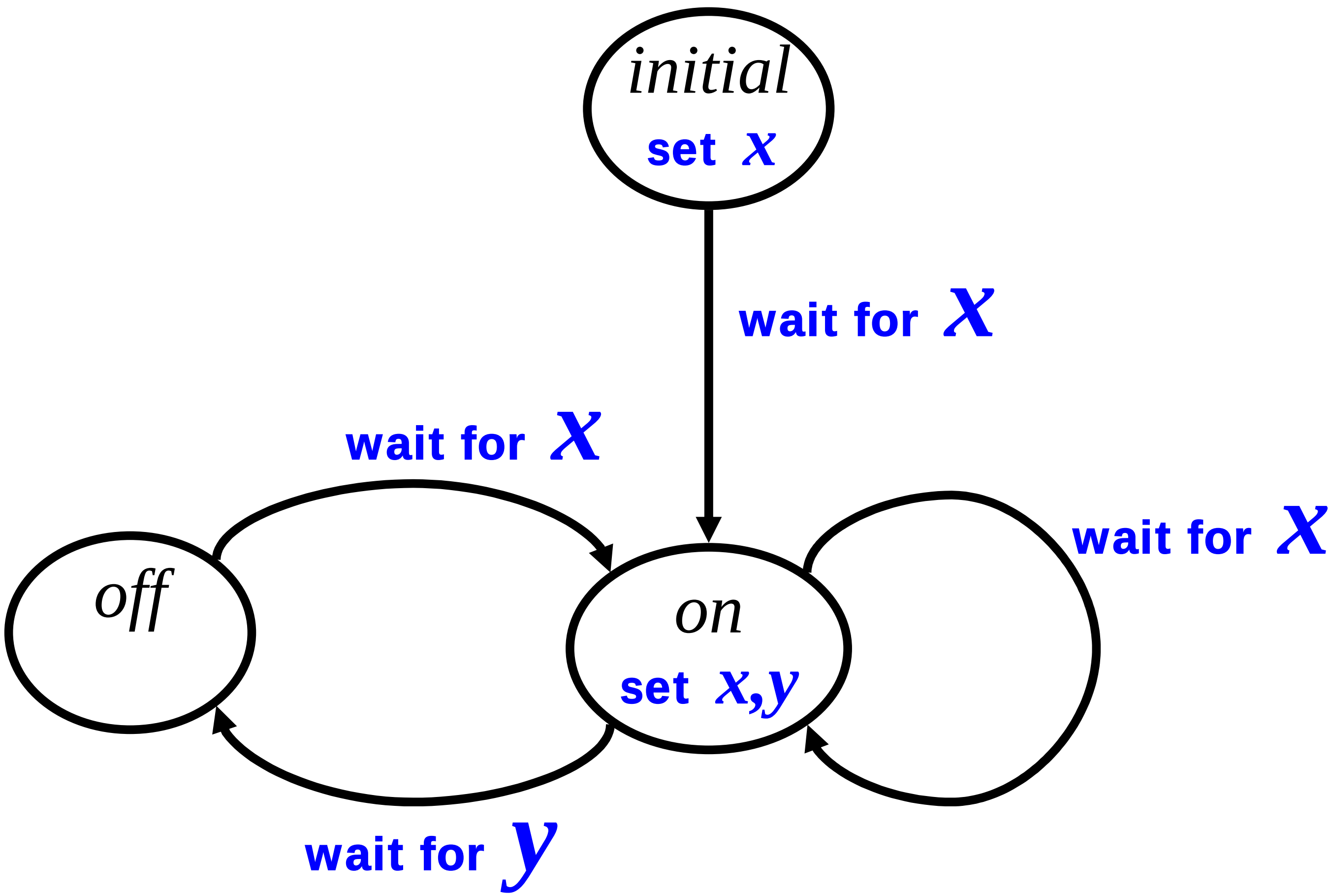
  it makes life (i.e. modelling and analysis) *a lot* simpler;

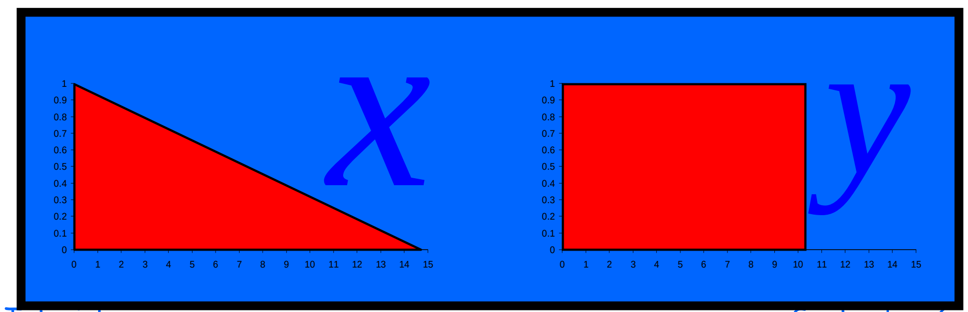
- and:

  it is often an appropriate simplification.

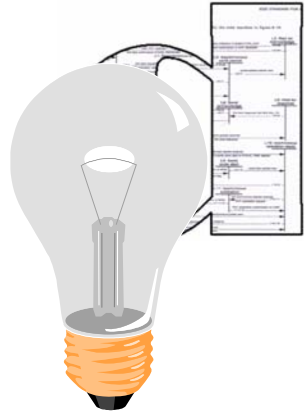
Beyond Markov Chains: Stochastic models *with* memory

- states, transitions
- labels
  - of states
  - of transitions
- *clocks*
  - serve as the memory of time.
  - are sampled from distributions, count down

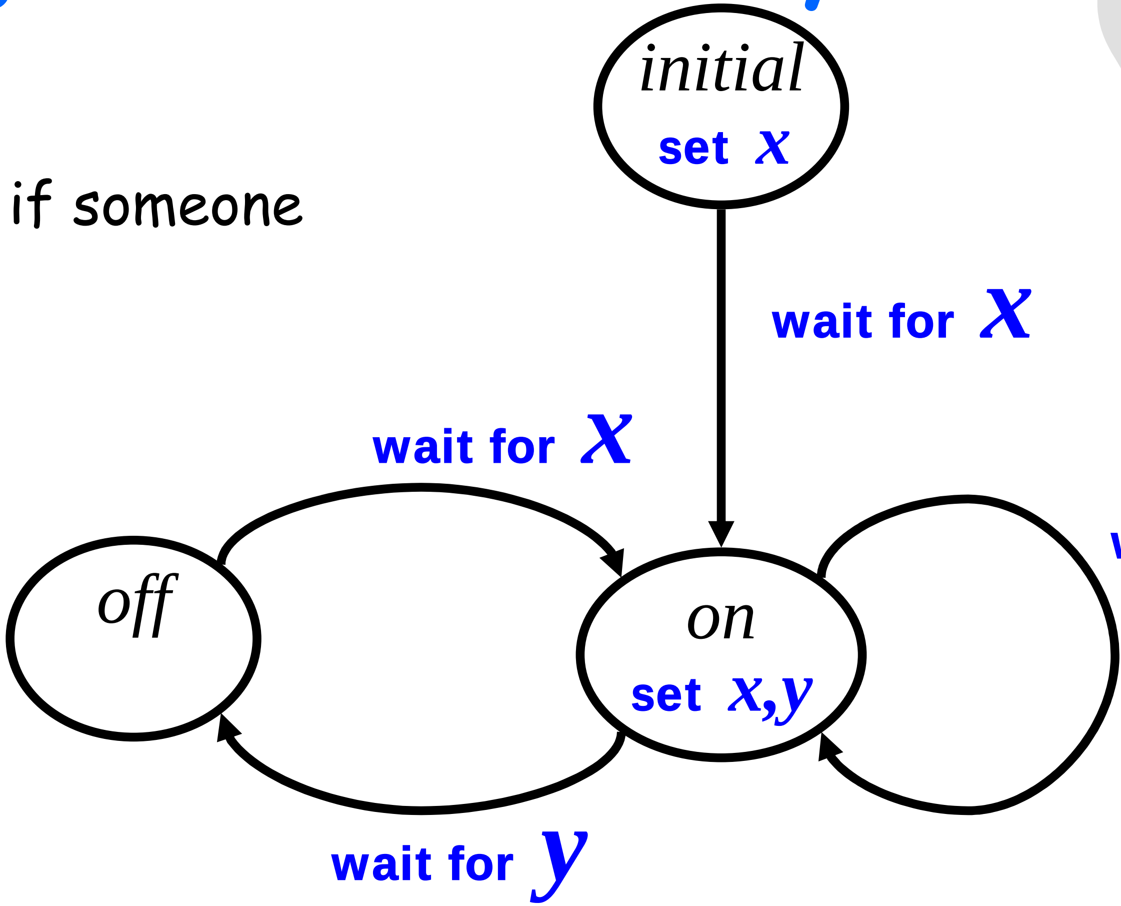




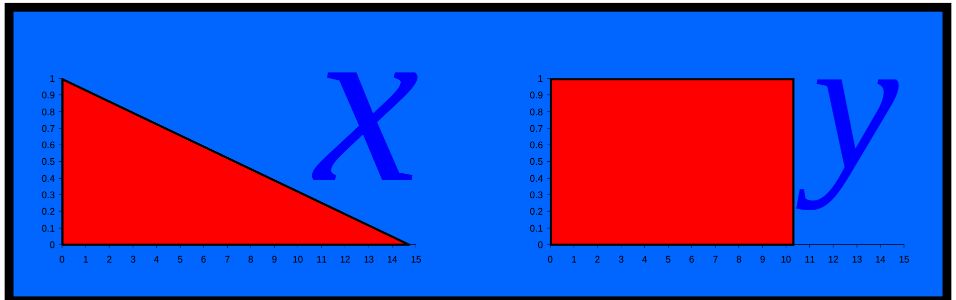
A light in the stairway



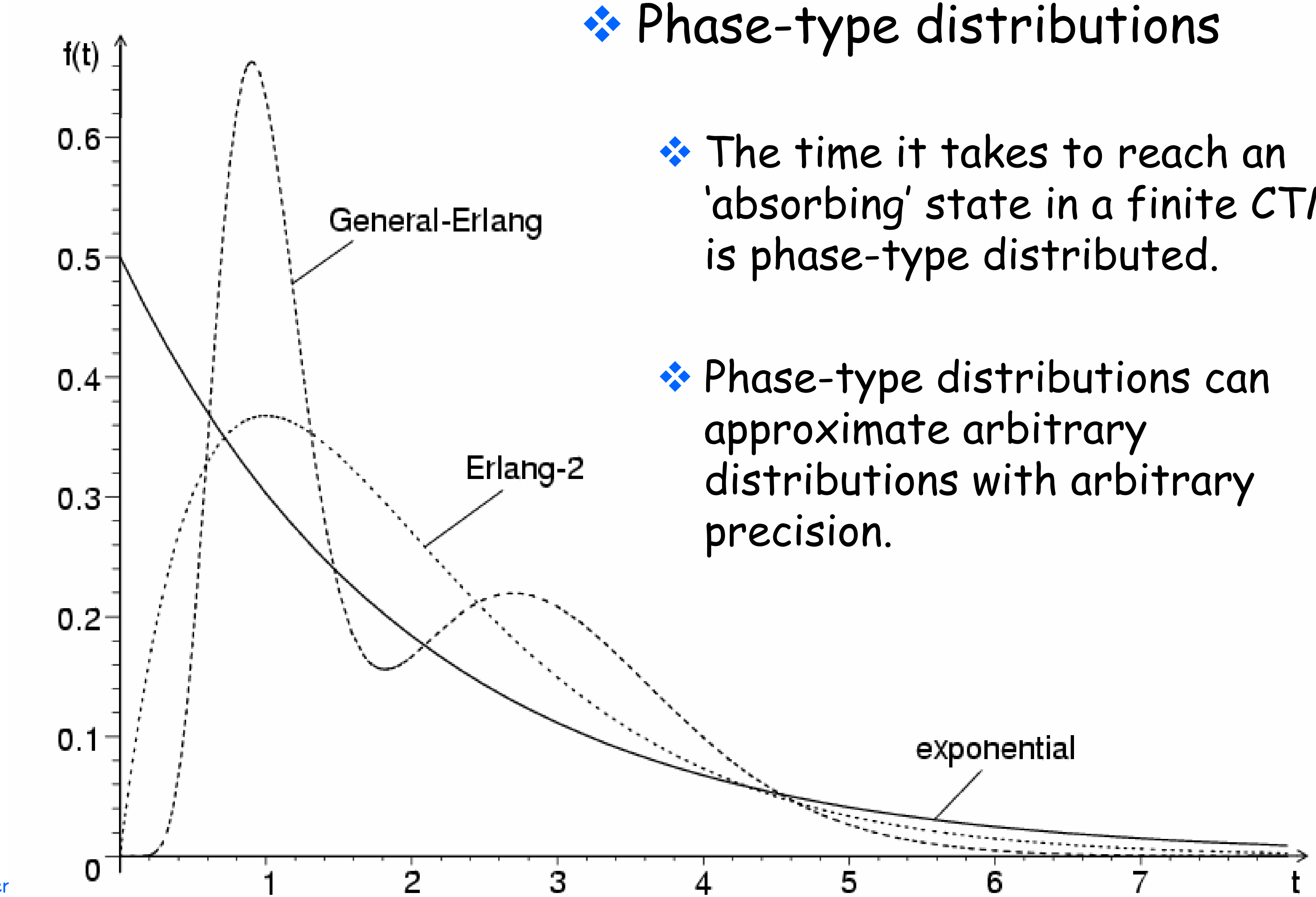
- The light is turned *on* if someone enters the stairway.
- It goes *off* after exactly 10.3 minutes.



- People arrive randomly, at least every 15 minutes, with equal probability for each time instant.



Virtually beyond Markov Chains



- Phase-type distributions
  - The time it takes to reach an 'absorbing' state in a finite CTMC is phase-type distributed.
  - Phase-type distributions can approximate arbitrary distributions with arbitrary precision.

Stochastic models

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A snackbar in Eindhoven (revisited)

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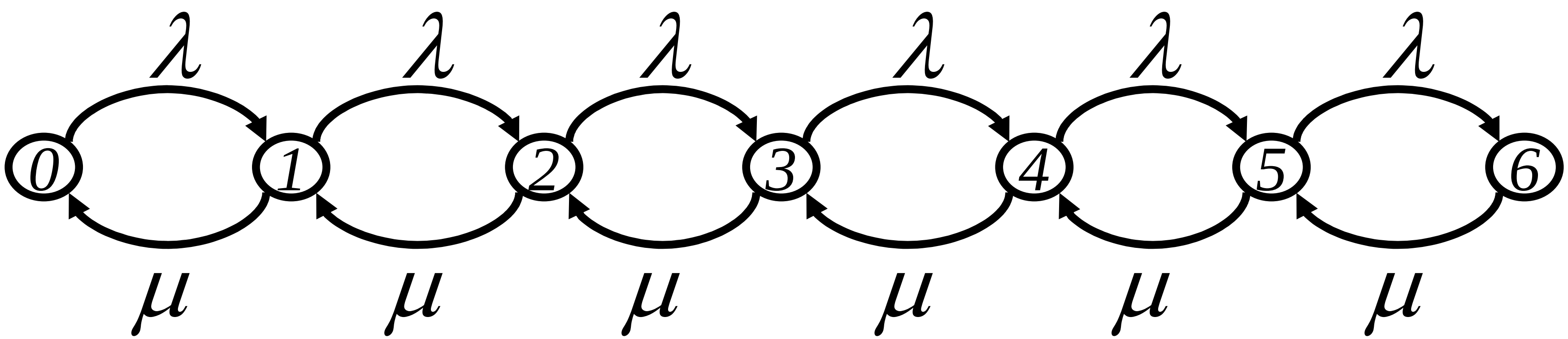


Snackbar (cont.)

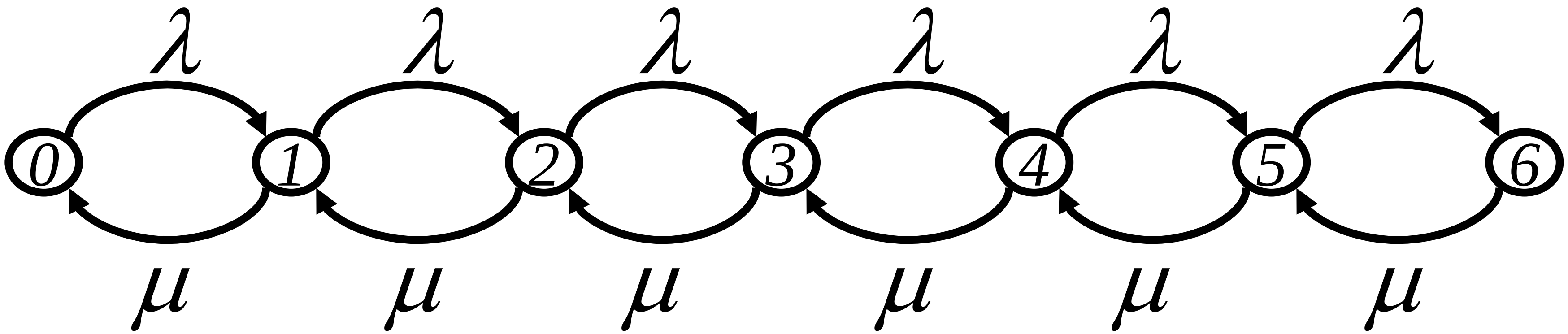
What's the utilization of the snackbar?

Solve

$$\tilde{\mathbf{Q}}\pi = 0$$

$$\sum_s \pi(s) = 1$$

$$\tilde{\mathbf{Q}} = \begin{bmatrix} -\lambda & \lambda & 0 & 0 & 0 & 0 & 0 \\ \mu & -\lambda-\mu & \lambda & 0 & 0 & 0 & 0 \\ 0 & \mu & -\lambda-\mu & \lambda & 0 & 0 & 0 \\ 0 & 0 & \mu & -\lambda-\mu & \lambda & 0 & 0 \\ 0 & 0 & 0 & \mu & -\lambda-\mu & \lambda & 0 \\ 0 & 0 & 0 & 0 & \mu & -\lambda-\mu & \lambda \\ 0 & 0 & 0 & 0 & 0 & \mu & -\mu \end{bmatrix}$$



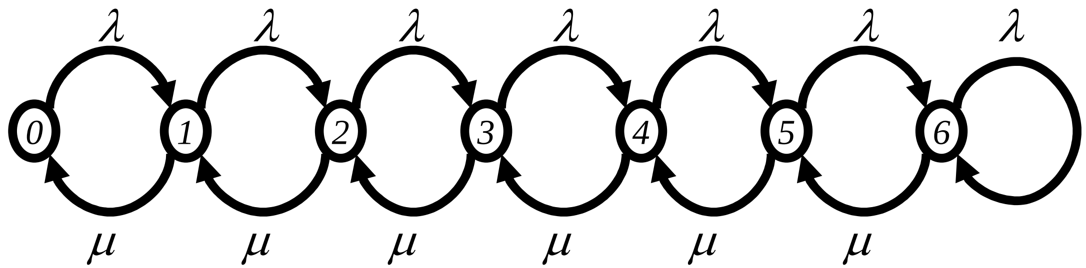
Analysing stochastic models

What would you like to know?

- **Or**, what is your measure of performance?
  - mean number of customers waiting in the snackbar?
  - mean time a customer has to wait?
  - percentage of time snackbar is utilised by someone?
  - number of customers served per minute?
  - percentage of customers that are lost, due to lack of space?
  - profit made?
  - number of wealthy customers lost?
  - ...

Standard performance measures

- mean queue length,
- mean waiting time,
- throughput,
- probability of loss,
- utilization

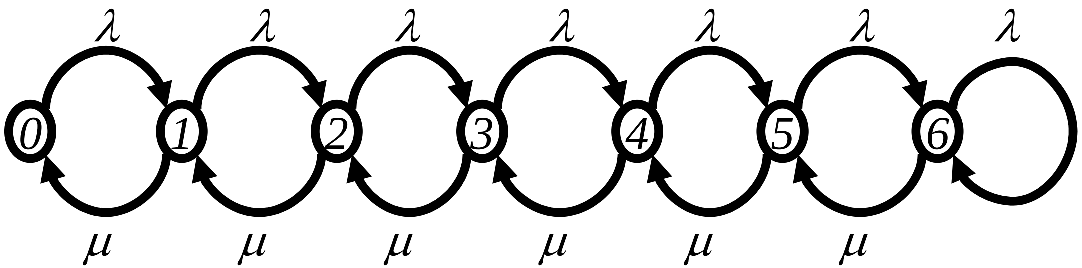


... and fault tolerance measures

- mean time to system failure,
- mean time between failures,
- system availability,
- ...

Calculating performance measures

- all these performance (and fault tolerance) measures can be computed on the basis of
  - state probabilities,
  - state labels, and/or
  - transition labels.



- Computation of *state probabilities* is the main technical issue.

- Recall: state probabilities describe the likelihood of being in a certain state (at a certain time instant)

Calculating state probabilities

- There are three fundamentally different ways to calculate state probabilities
  - *analytical* solution,
  - *numerical* solution,
  - *simulation*.

Analytical solution

- express the state probabilities (or even measures directly) as *closed formulae* in the parameters of the model

example: utilization of the snackbar $U(\lambda,\mu) = \lambda / \mu$

provided that $\lambda<\mu$, and that the queue length may become larger than 6, namely infinite

- *pros:*
  - very accurate
  - very fast, and simple

- *cons:*
  - only for highly restricted classes of stochastic processes
  - requires study of scientific literature, to find specific formulae

Numerical solution

- state probabilities are obtained by an exact algorithm where model parameters are instantiated with numerical values.

example: state probabilities of the snackbar are obtained by (e.g.) Gauss elimination of a 7×7 matrix based on $1/3$ and $1/5$ entries.

- *pros:*
  - accurate, up to numerical precision
- *cons:*
  - only reasonable for finite *Markov chains*
  - number of states is a limiting factor (about 10^8)

Simulation

- the stochastic model is mimicked by a simulator rolling dices and producing statistics of *simulation time* spent in states. The fraction of *simulation time* spent in a particular state is used as an estimate for the state probability.

example: Let a lot of (virtual) people use the (virtual) light bulb, and compute the fraction of time where the light is on.
Do this 100000 times faster than real time.

- *pros:*
  - very general, suitable for arbitrary stochastic models

- *cons:*
  - good accuracy usually requires long (often very long) simulation runs

Rules of thumb

- *Analytical solution* allows very *quick* and very *precise* insight in your model, but the model tends to be a very *loose approximation* of reality.

- *Simulation* allows relatively *slow* and *rough* insight in a *single* instance of your model, but the model can have a *close correspondence* to reality.

- *Numerical solution* allows *quick* and *precise* insight in a *single* instance of your *Markov chain* model, which usually is an *approximation* of reality (due to absence of memory).

Stochastic modelling and analysis

The standard procedure:

- construct a model (...),
- determine your performance measure of interest,
- choose a solution method:
  - analytical,
  - numerical, or
  - simulation,
- fix model parameters (λ,μ,...),
- derive measure.

play with the model

Why play with model parameters?

- to pose "what if" questions

    perturbation analysis

- to see how performance changes if parameters change

    sensitivity analysis

- to find the best performance (tuning)

    optimisation

Rules of thumb revisited

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- *Numerical solution* allows *quick* and *precise* insight in a *single* instance of your *Markov chain* model, which usually is an *approximation* of reality (due to absence of memory).

In order to *optimise* (etc.) that computation has to be repeated many times

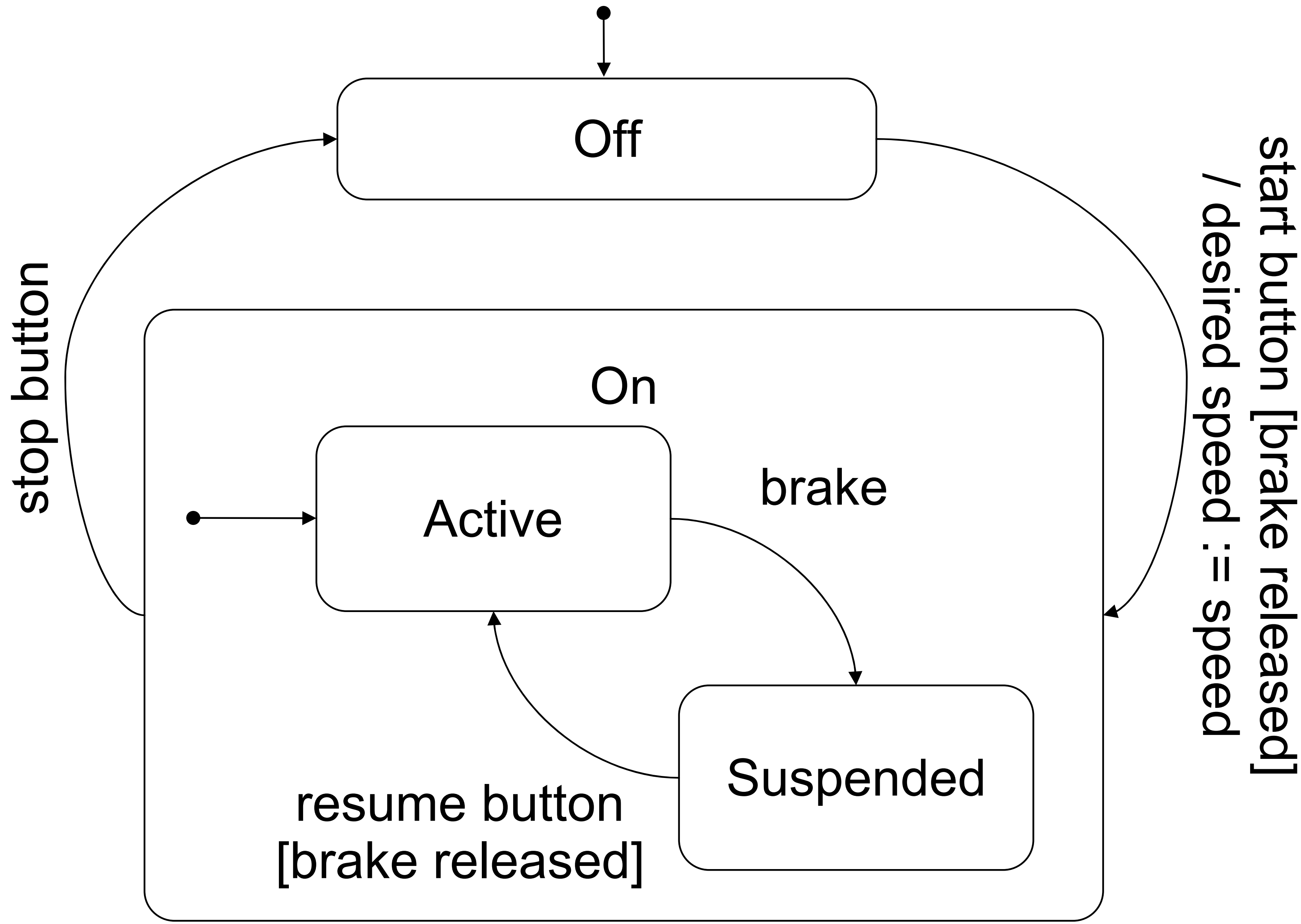
Overview

- Introduction to QoS modeling and analysis
- Introduction to Statecharts
- StoCharts
  - Introduction
  - Semantics
  - Applications
- Conclusions and future outlook

Statecharts

Material courtesy of David N. Jansen

Example: Cruise Control



Basic Ideas

- Statecharts :=

  finite state machines +

  hierarchy +

  parallel behaviours

- Originally developed by David Harel
  - Harel: *Statecharts: a visual formalism for complex systems.* Science of computer programming 8(1987), pp. 231–274.

Possible Uses

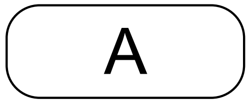
- Control automata of embedded systems
  - developed to specify avionics of an Israeli aircraft
  - also used e. g. in automotive systems
- Object life cycle in OO software
  - part of the UML
- Protocol specification
  - in UML 2.0

Tools and Methods

- Commercial and research tools available
  - Statemate
  - several UML tools, e. g. Rhapsody
- There are many variants
  - RSML
  - Stateflow
  - Argos / SyncCharts
  - UML Statecharts
- Used in industry
  - e. g. by DaimlerChrysler, Siemens, Airbus

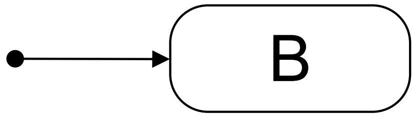
Basic Syntax

- Nodes

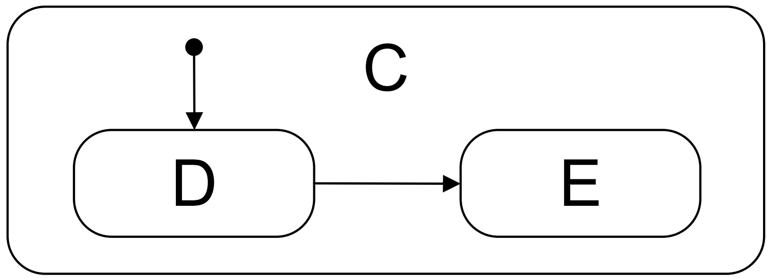


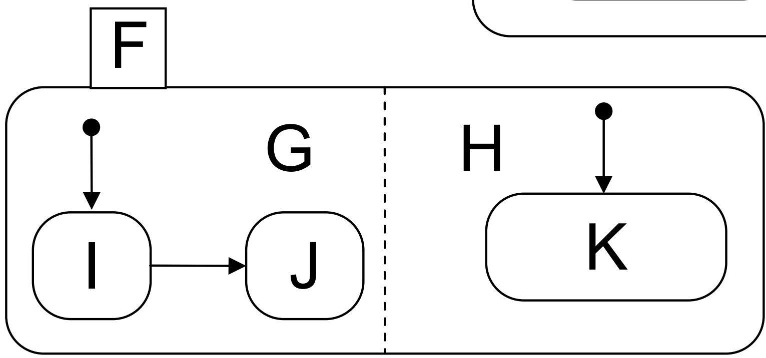
- Transitions

- Initial node



- OR nodes



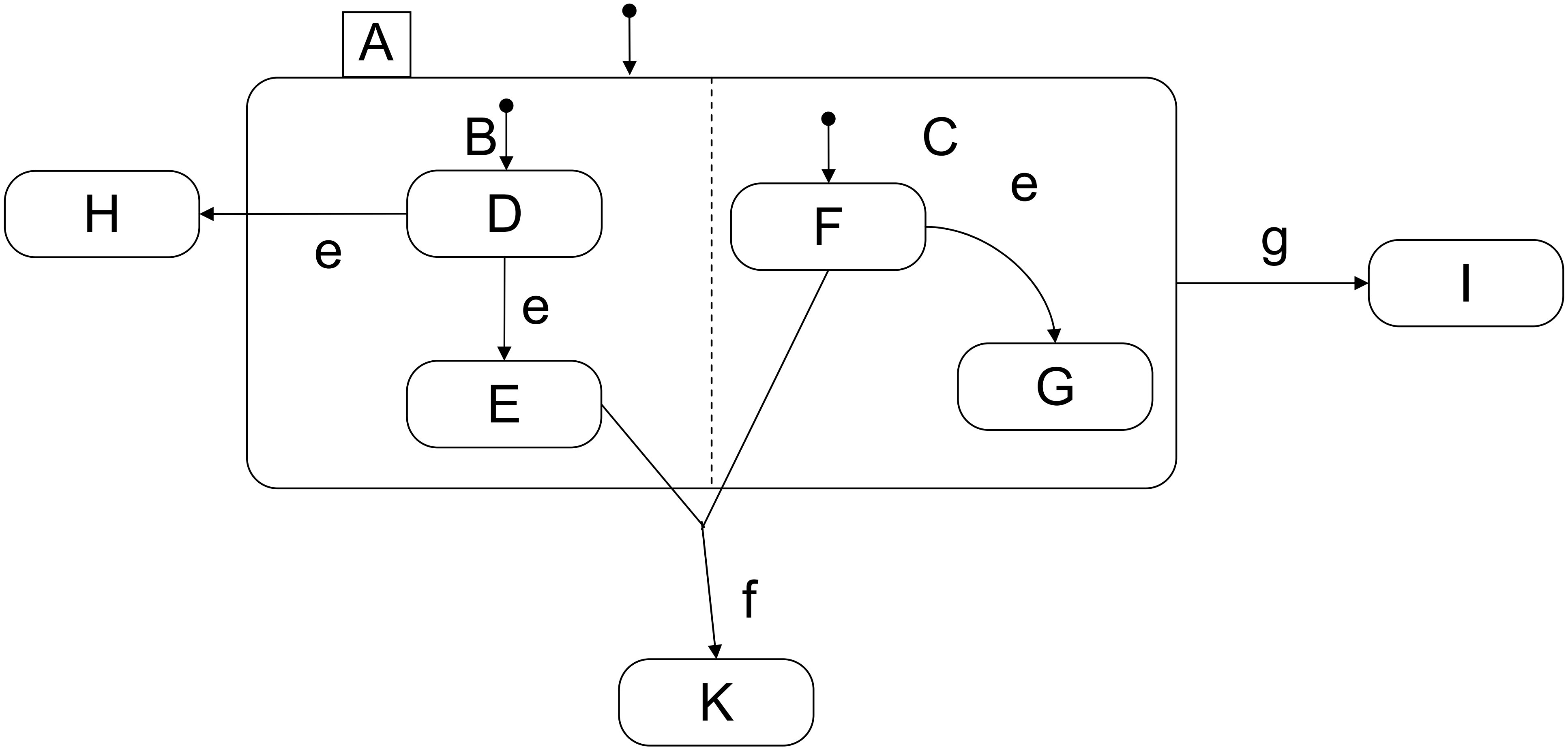


- AND nodes

Informal Semantics

- The system is always in a configuration
  - Configuration := set of nodes
    (multiple nodes if there is parallelism)
- Upon reception of an event, it takes a step
  - Step := set of transitions that are taken simultaneously
    (multiple transitions if there is parallelism)
- The system...
  - leaves the source node(s)
  - executes the actions of the transitions
  - enters the target node(s)

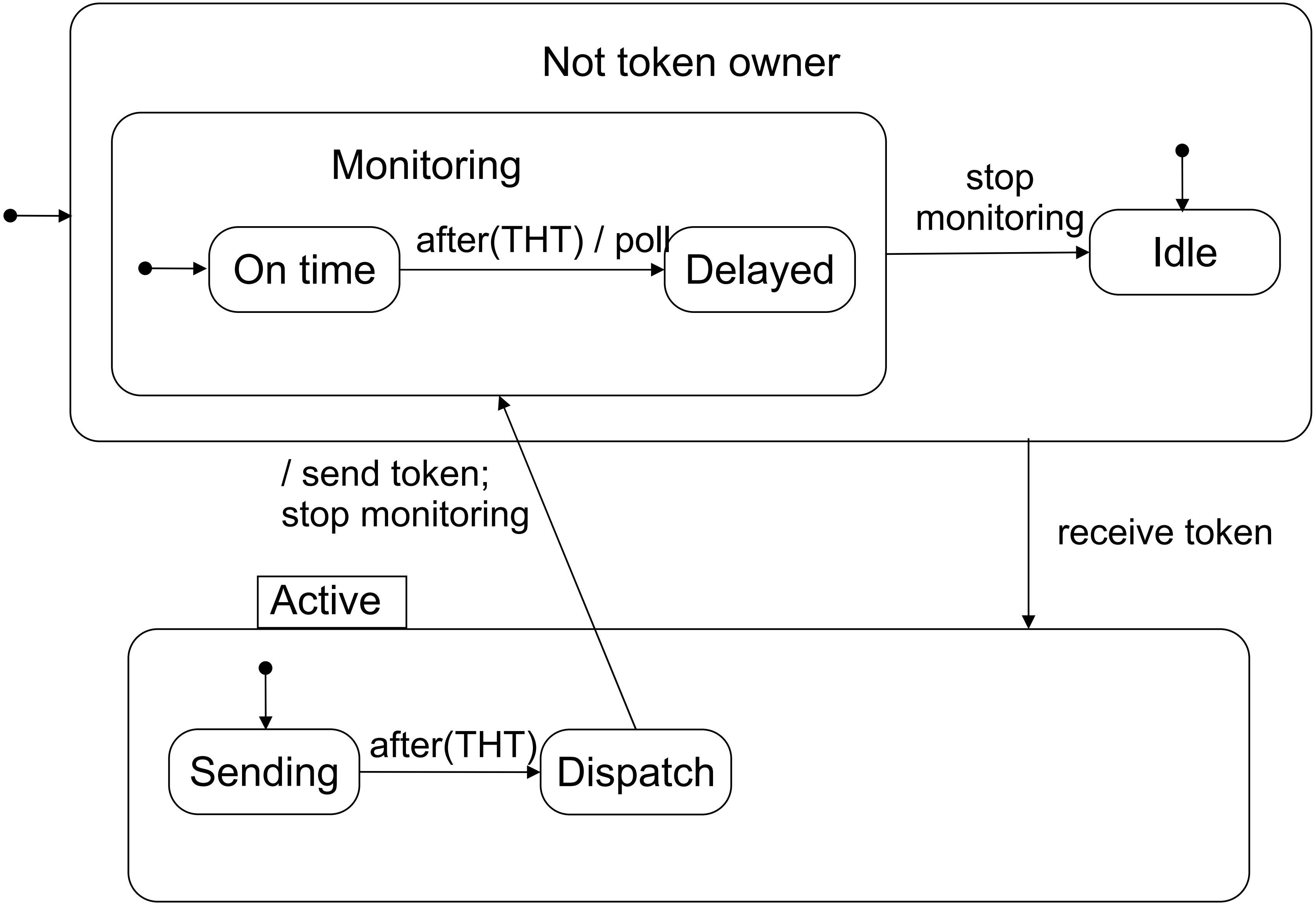
Some Intricacies



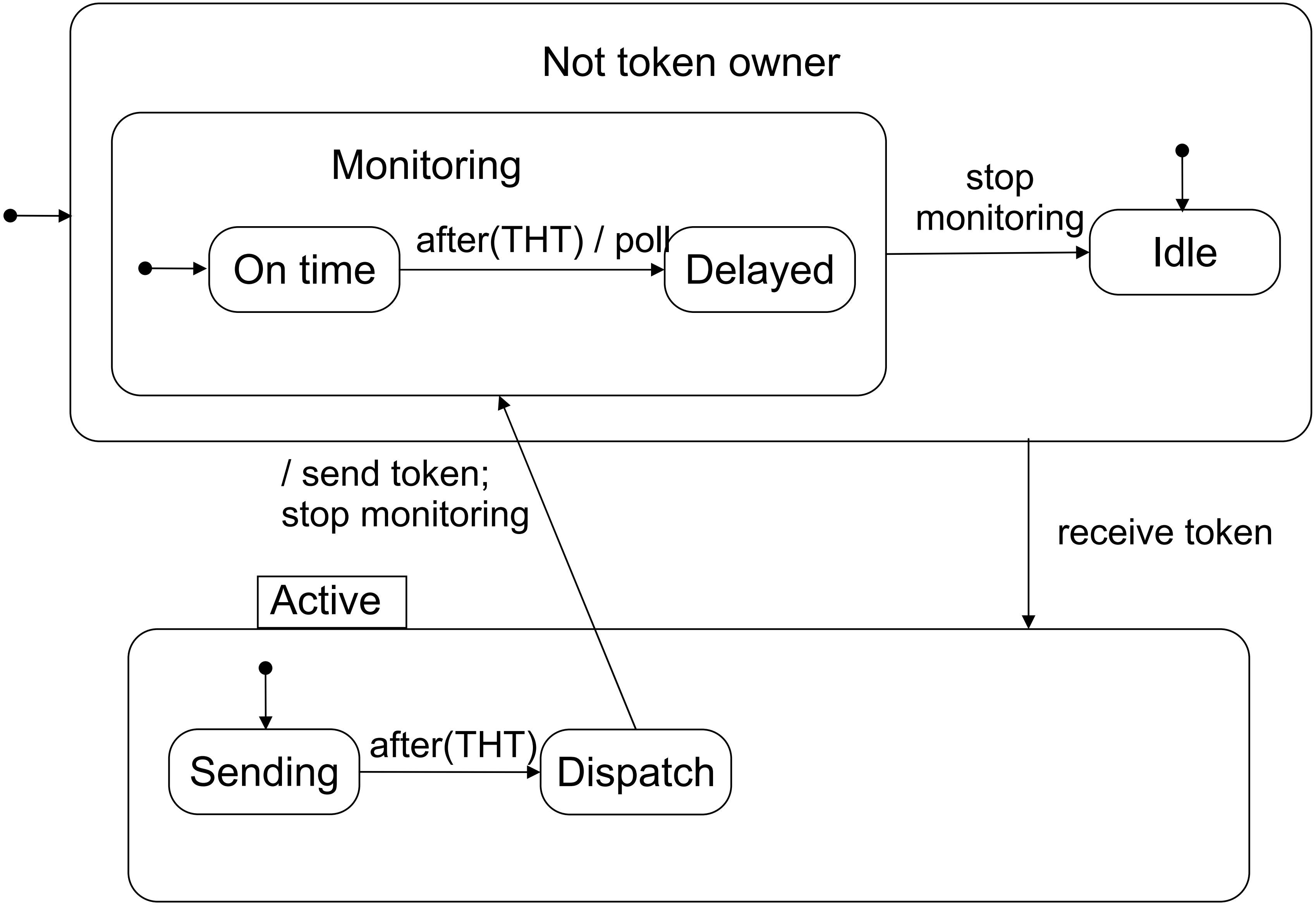
Example: RTnet Protocol

- RTnet is a simple realtime network
  - nodes share the bandwidth of the network
  - real-time guarantees
- A token is passed around
  - Its owner may send data for some time (THT)
- The monitor checks the active node
  - After being active node, a node becomes monitor
  - If the new active node dies,
    the monitor reconfigures the system

Example: RTnet Protocol



Assignement: RTnet Protocol

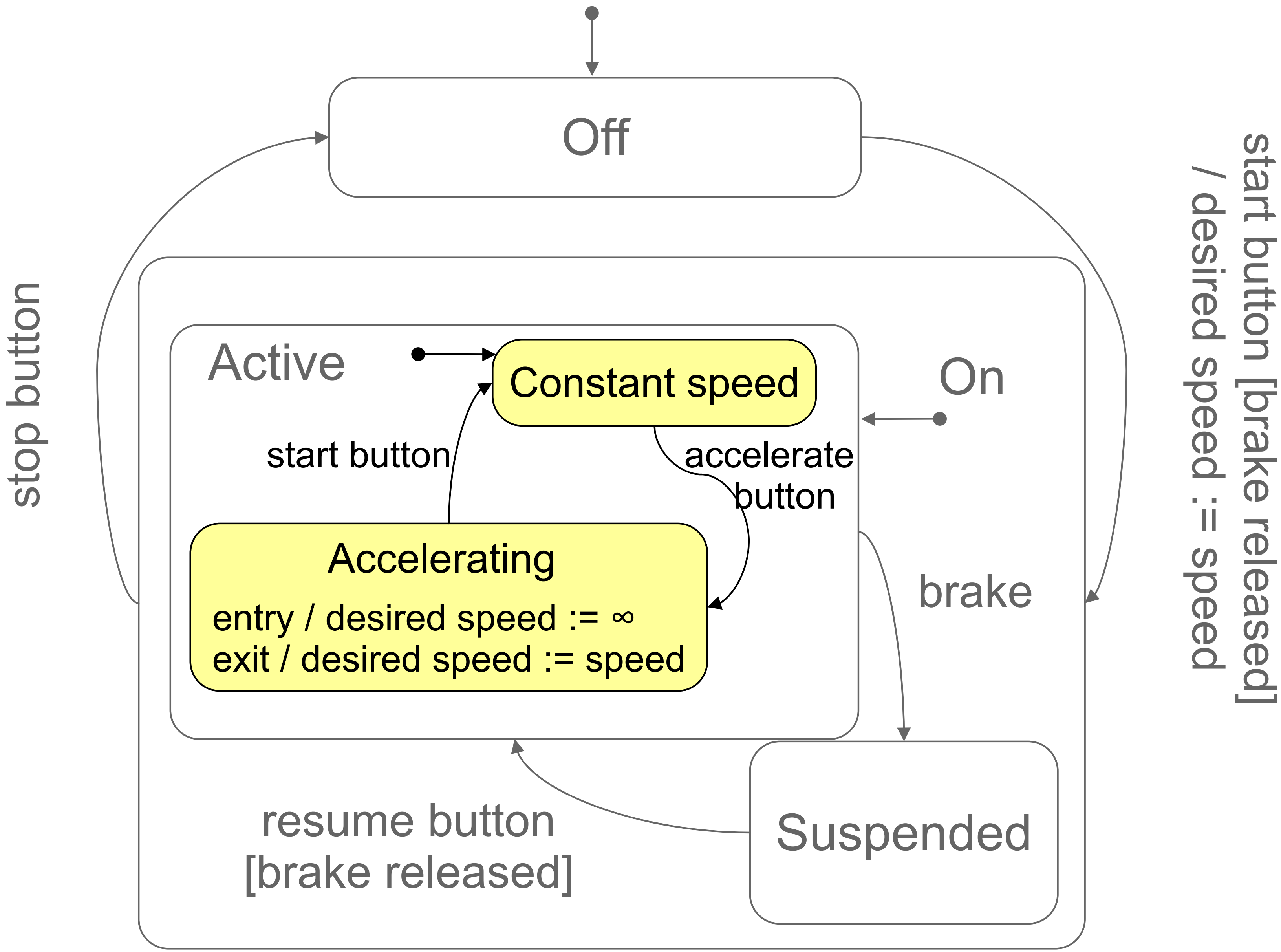


Object-Oriented Statecharts

- Statecharts for object life cycles
- variant of Statechart semantics
  - Harel / Gery: *Executable object modeling with Statecharts.* Computer, July 1997, pp. 31–42.

- Inheritance / overriding of behaviour?
  - Yes: refine states
  - Perhaps: redirect transitions
  - No: change transition triggers
- Priorities in accordance with inheritance

Example of Behaviour Inheritance



Run-To-Completion Semantics

- procedure call-like definition of transition:
  - One transition may invoke another transition
  - State of the invoking Statechart is undefined during this invocation
  - may lead to deadlock
- We recommend to abandon this semantics

Semantics of Statecharts

Material courtesy of Joost-Pieter Katoen

What is a UML StateChart?

A UML StateChart $SC = (\mathit{Nodes}, \mathit{Ev}, \mathit{Edges})$ with:

- A set *Nodes* of *nodes* structured in a tree
- A (finite) set *Ev* of *events*
  - there is a pseudo-event $\mathit{after}(d)$ denoting a delay of d time units
  - $\perp \notin \mathit{Ev}$ stands for “no event”
- A (finite) set *Edges* of edges (in fact, *hyperedges*)

Syntactic sugar

this is an elementary form; the UML allows more constructs
that can be defined in terms of these basic elements

- Deferred events — simulate by regeneration
- Parametrised events — simulate by set of parameter-less events
- Activities that take time — simulate by start and end event
- Dynamic choice points — simulate by intermediate state
- Synchronization states — use a hyperedge with a counter
- History states — (re)define an entry point

More about nodes

- Nodes are structured in a *tree*
  - *children*(x) is the set of children of node x
  - *root* is the unique root node of
  - $x \trianglelefteq y$ means node x is a descendant of node y
- Nodes are *typed*, *type*$(x) \in \{\, \textsc{Basic}, \textsc{And}, \textsc{Or} \,\}$ such that:
  - the root node is of type Or
  - each leaf node is of type Basic
  - each child of an And-node is of type Or
  - each Or-node has a *default* (initial) node

Edges

An *edge* is a tuple (X, e, g, A, Y), notation $X \xrightarrow{e[g]/A} Y$, where

- X and Y are non-empty sets of nodes
- X is the source and Y the target
- $e \in$ *Ev* is the trigger event
- g is a guard, i.e., a Boolean expression
- A is a set of actions (such as *send* $j.e$ or $v :=$ *expr*)

“if currently in X and g holds, on occurrence of e,
actions A can be performed while evolving into Y”

Assumptions in our semantics

adopted from [Eshuis & Wieringa 2000]

- Input is event *set* (and not a queue)
- System reacts to all input events ($\neq$ first); not consumed events “die”
- Instantaneous communication and instantaneous actions
- Unlimited concurrency
- Perfect communication (no loss)
- System reacts to internal events generated in step i in step $i{+}1$
  - this is called a sequential step semantics

  $\Rightarrow$ yields a causality-preserving semantics

What does a single StateChart mean?

Intuitive semantics as a transition system:

- State = one or more nodes ("current control") + the values of variables
- Edge is enabled if guard holds in current state
- Executing an edge = perform actions A, consume event e,
  - leave source state and switch to target state

  $\Rightarrow$ events are unordered, and considered as a set
- Principle: execute as many edges at once (without conflict)

  $\Rightarrow$ this is called a *step*

How to compute a step?

States and configurations

- A *configuration* C is a set of nodes satisfying
  - *root* $\in C$
  - for each OR-node in C, there is a *unique* child in C
  - for each AND-node in C, all children are in C

- *State* (C, I, V) is a tuple where
  - C is a configuration
  - $I \subseteq$ *Ev* is the set of events to be processed
  - V is the valuation of the variables

Enabling of an edge

Edge (X, e, g, A, Y) is *enabled* in state (C, I, V) whenever:

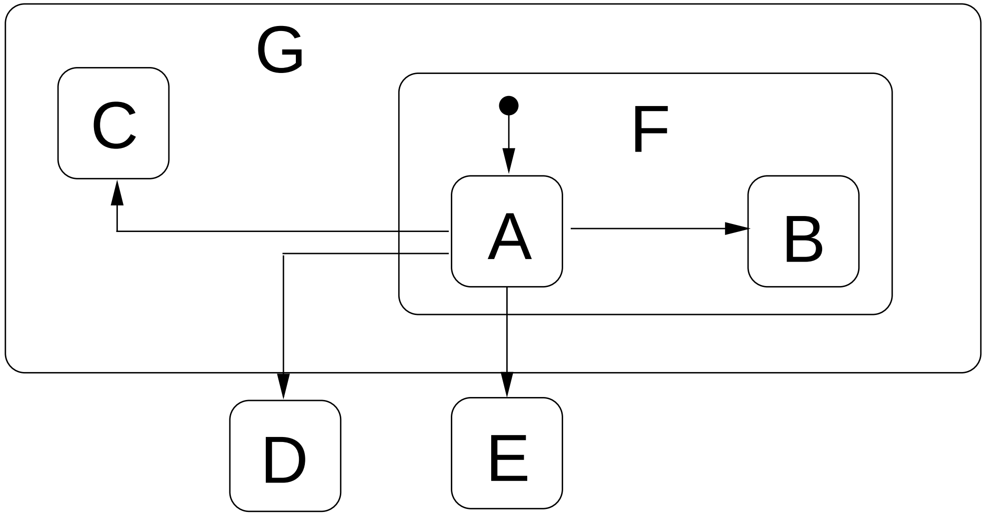
- $X \subseteq C$, i.e. all source nodes are in configuration C
- guard g holds in C_1 through C_n with events I_1 through I_n
- $e \in I$, i.e. the input event needs to be present (or equals $\perp$)

En(C, I, V) denotes the set of enabled edges in state (C, I, V)

Scope of an edge

Scope of edge $X \xrightarrow{\cdots} Y$ = *most nested* OR-node containing X *and* Y

The most nested node that is *unaffected* by executing the edge



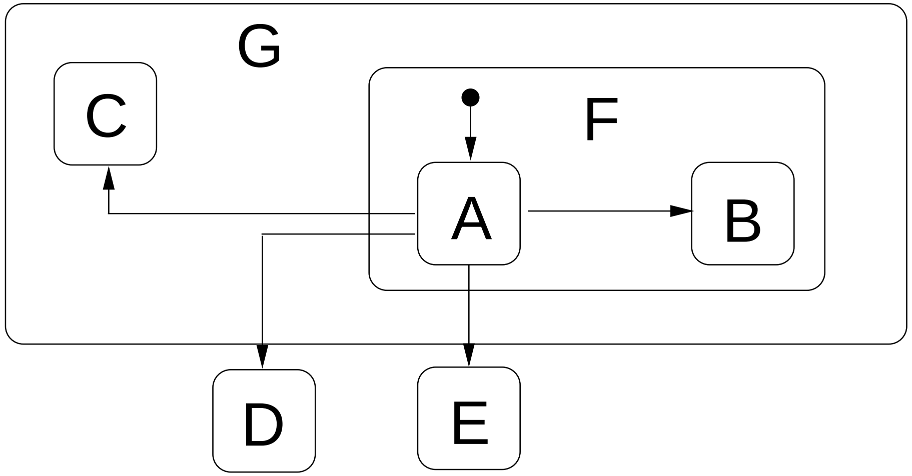
$$\mathit{scope}(A \rightarrow D) = \mathit{root} \quad \text{and} \quad \mathit{scope}(A \rightarrow C) = G \quad \text{and} \quad \mathit{scope}(A \rightarrow B) = F$$

Priority

Priority is a partial order on edges; different priority schemes exist, e.g.

$$\textit{prio}(ed) \geqslant \textit{prio}(ed') \quad \text{if} \quad \textit{scope}(ed) \trianglelefteq \textit{scope}(ed') \qquad \text{UML}$$

$$\textit{prio}(ed) \leqslant \textit{prio}(ed') \quad \text{if} \quad \textit{scope}(ed) \trianglelefteq \textit{scope}(ed') \qquad \text{STATEMATE}$$



$\textit{prio}(A \rightarrow C) > \textit{prio}(A \rightarrow D)$ since $\textit{scope}(A \rightarrow C) = G \trianglelefteq \textit{root} = \textit{scope}(A \rightarrow D)$

What is now a step?

A step is a *set of enabled edges* such that:

- all edges in a step are enabled
- all edges are pairwise consistent
  - they are identical or
  - scopes are (descendants of) different children of the same AND-node
- enabled edge ed is not in step implies

  $\exists ed' \in$ step. (ed inconsistent with ed' and $\not($*prio*$(ed') <$ *prio*$(ed)))$

- a step must be maximal (wrt. set inclusion)

Computing the set T of steps

Initialize $T := \varnothing$

While

there is an enabled edge in *En*$(C, I, V) - T$
which is consistent with all edges in T

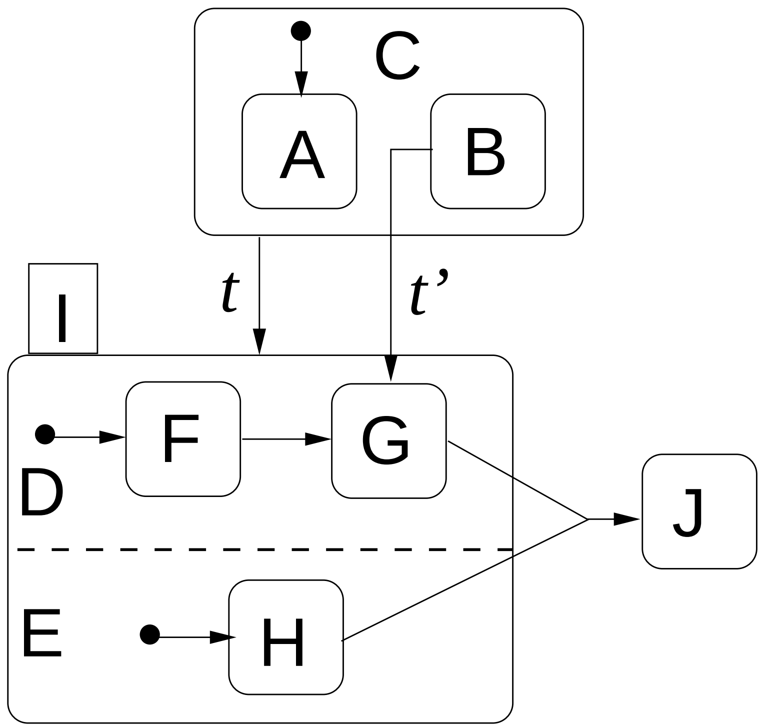
Do

choose one of these edges which has maximal priority
and add this edge to T

Return T

Steps(*En*(C, I, V)) denotes the set of steps in state (C, I, V)

Executing a step



$$\{\,\textit{root}, A, C\,\} \xrightarrow{\{\,t\,\}} \{\,\textit{root}, I, D, E, F, H\,\}$$

i.e., the *default completion of* $\{\,\textit{root}, I\,\}$

Notation: $\textit{Exec}(C_{1..n}, T_{1..n}) = ((C_1', I_1', V_1'), \ldots, (C_n', I_n', V_n'))$

I/O automata

[Lynch & Tuttle 1987]

An *input-output automaton* is a tuple $(L, \ell_0, A, \longrightarrow)$ with

- L is a finite non-empty set of locations with initial location $\ell_0 \in L$
- A is a set of actions partitioned into A^{in} and A^{out}
- $\longrightarrow \subseteq L \times A \times L$, the transition relation satisfying
  - for any $\ell \in L$ and $a \in A^{in}$, $\exists \ell' \in L$ such that $\ell \xrightarrow{a} \ell'$ *input enabledness*

as internal actions are not used here, they are omitted

From StateCharts to an I/O automaton

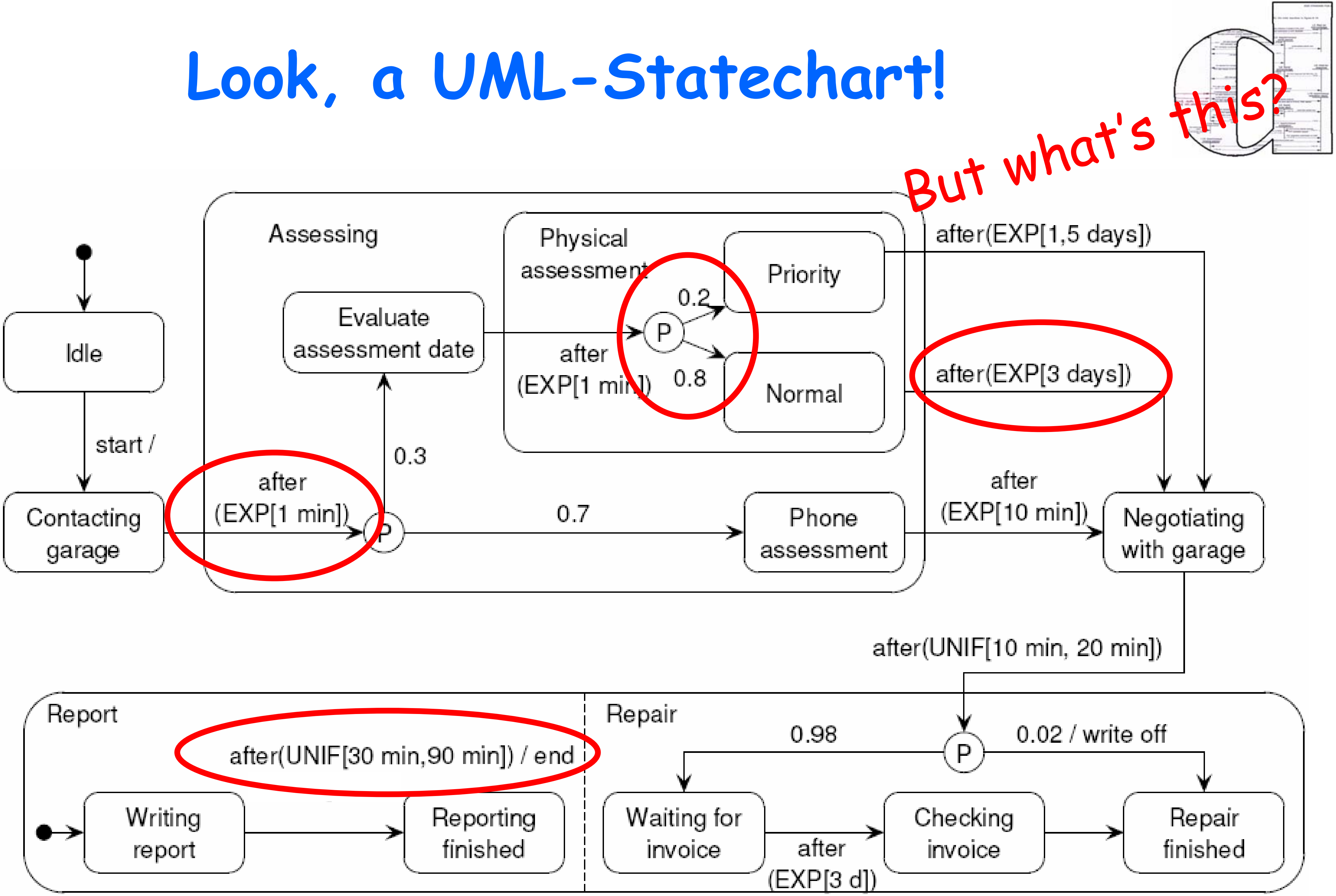
- $L = (\mathit{Conf}_1 \times 2^{\mathit{Ev}_1} \times \mathit{Val}_1) \times (\mathit{Conf}_2 \times 2^{\mathit{Ev}_2} \times \mathit{Val}_2)$
- $\ell_0 = ((C_{0,1}, \varnothing, V_{0,1}), (C_{0,2}, \varnothing, V_{0,2}))$
  - where $C_{0,i}$ is the default completion of $\{ \mathit{root}_i \}$
- $A^{in} = 2^{\mathit{Ev}_1 \cup \mathit{Ev}_2} - \{ \varnothing \}$
- $A^{out} = 2^E$ with $E = \{ \mathit{send}\ j.e \in \mathit{SC}_1 \cup \mathit{SC}_2 \mid j \neq 1, 2 \}$
- $\dfrac{E \in A^{in}}{(\ell_1, \ell_2) \xrightarrow{E} (\ell_1', \ell_2')}$ with $\ell_j = (C_j, I_j, V_j)$ and $\ell_j' = (C_j, I_j \cup (E \cap \mathit{Ev}_j), V_j)$
- $\dfrac{T_i \in \mathit{Steps}(\mathit{En}(s_i)) \quad \text{for all } i}{(\ell_1, \ell_2) \xrightarrow{E} \mathit{Exec}(C_{1..2}, T_{1..2})}$ with E = outputs in T_i sent to SC_j, $j \neq 1, 2$

Overview

- Introduction to QoS modeling and analysis
- Introduction to Statecharts
- StoCharts
  - Introduction
  - Semantics
  - Applications
- Conclusions and future outlook

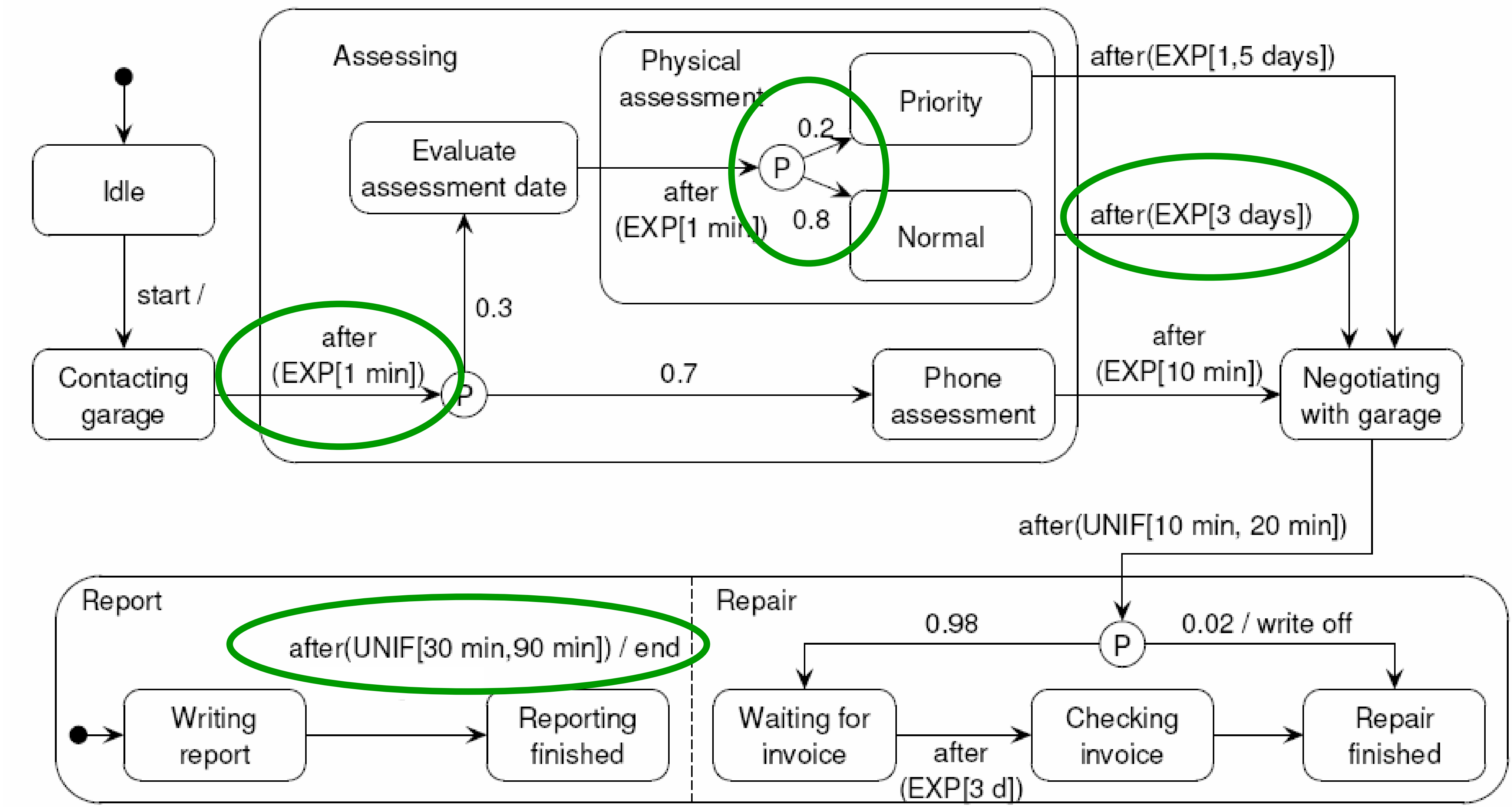
StoCharts

Look, a UML-Statechart!



It models a car damage assesment process.

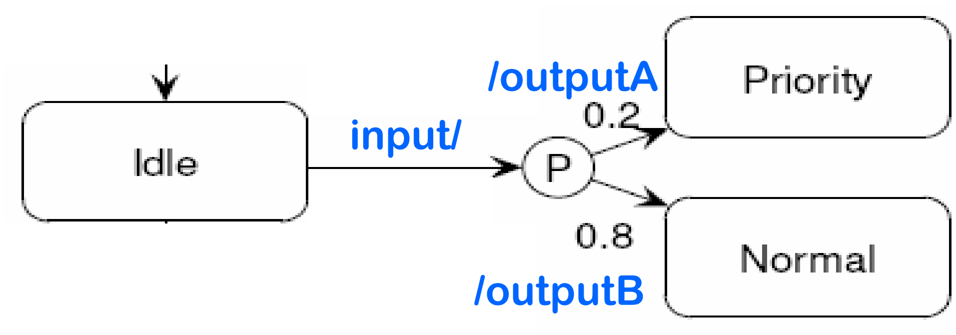
This Statechart has means to model stochastic phenomena



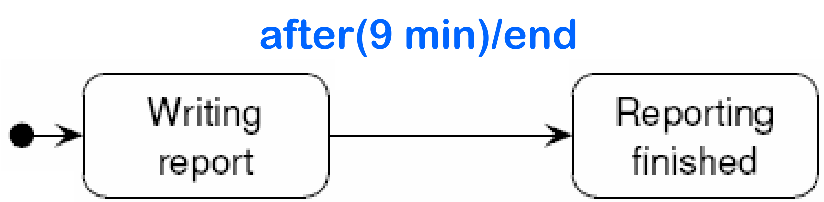
We call it a Stoc(hastic Statec)hart, or **StoChart** for short.

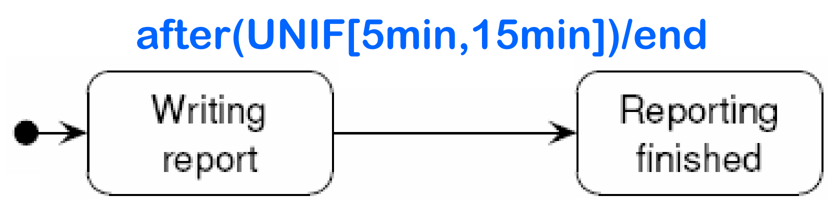
QoS primitives in StoCharts

- **Probabilistic branching**
  - restricted to the *effect* of edges (output)
  - input stays reactive & non-probabilistic
  - Notation uses a 'P-pseudonode' (denoted Ⓟ)

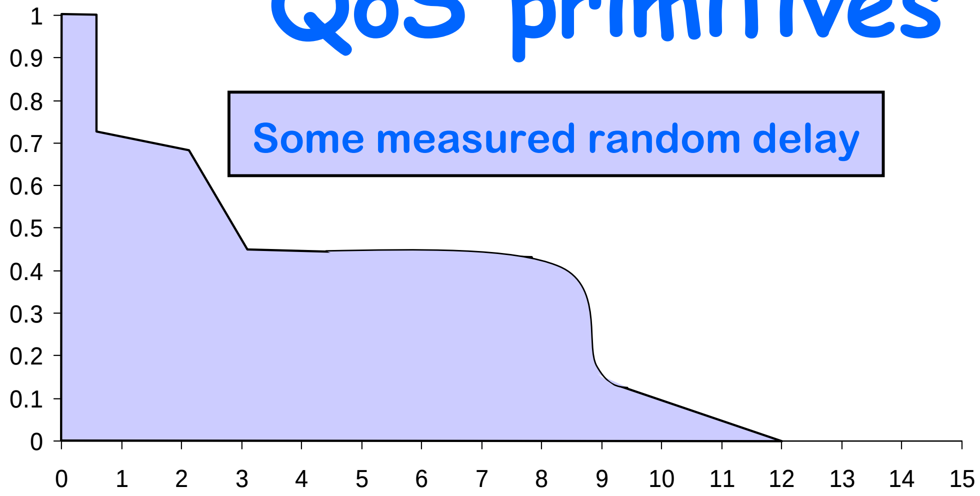


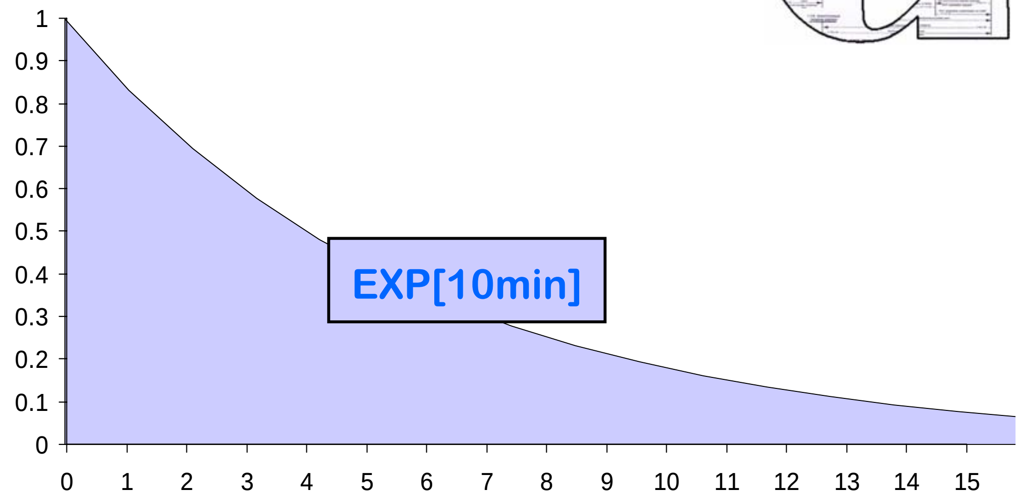
- **Random delays**
  - randomising the 'after'-construct of the UML

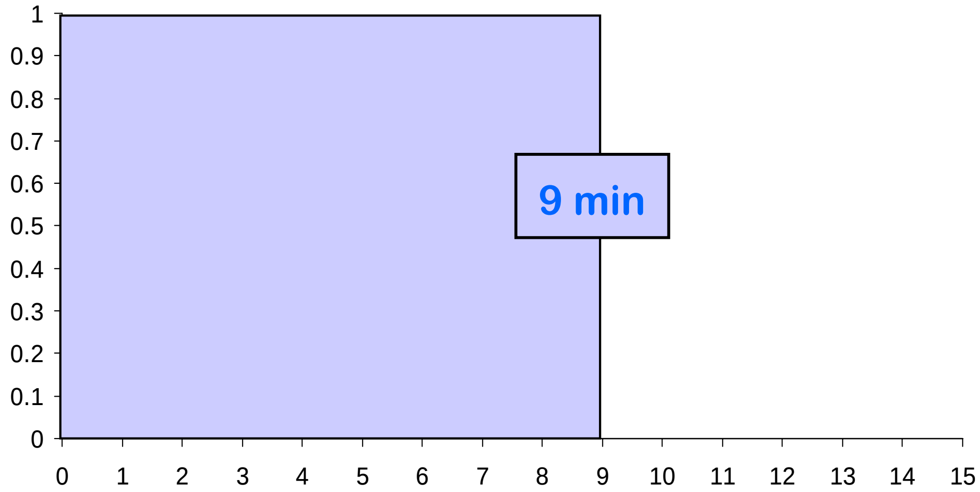


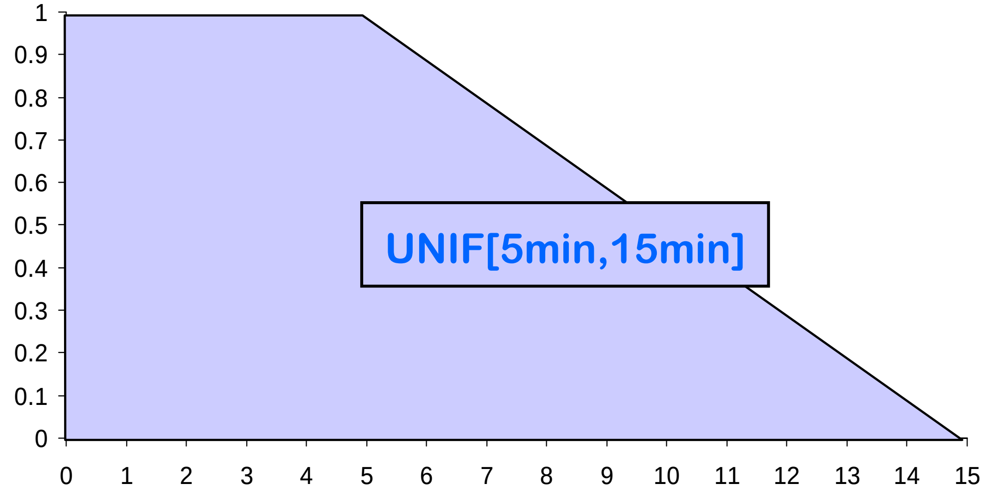


QoS primitives in StoCharts



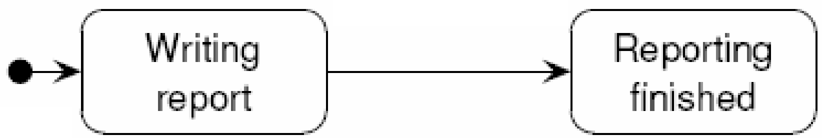




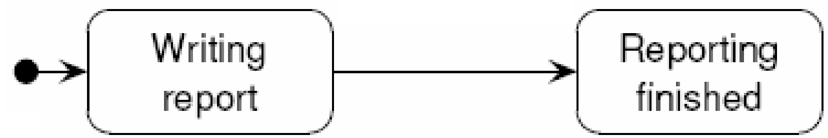


- **Random delays**
  - randomising the 'after'-construct of the UML

after(9 min)/end



after(UNIF[5min,15min])/end



QoS primitives in StoCharts

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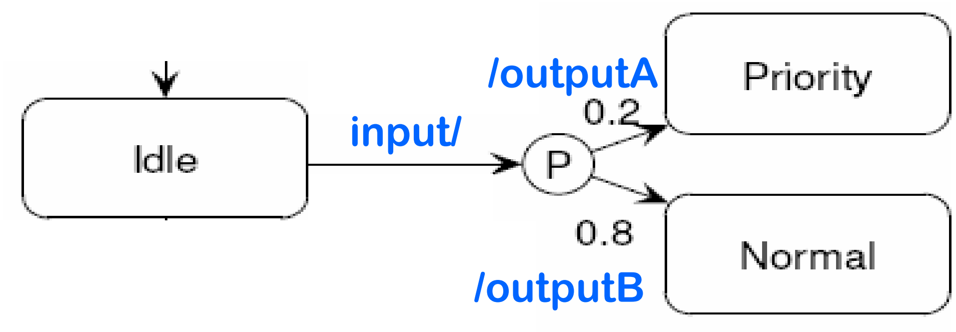
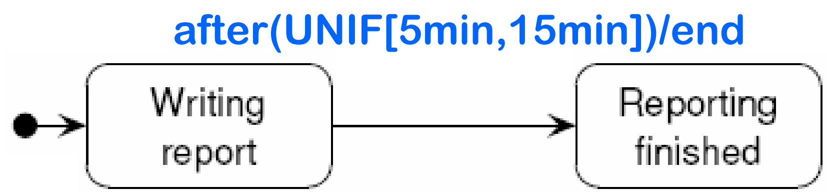


- **Random delays**
  - randomising the 'after'-construct of the UML



That's all.

Overview

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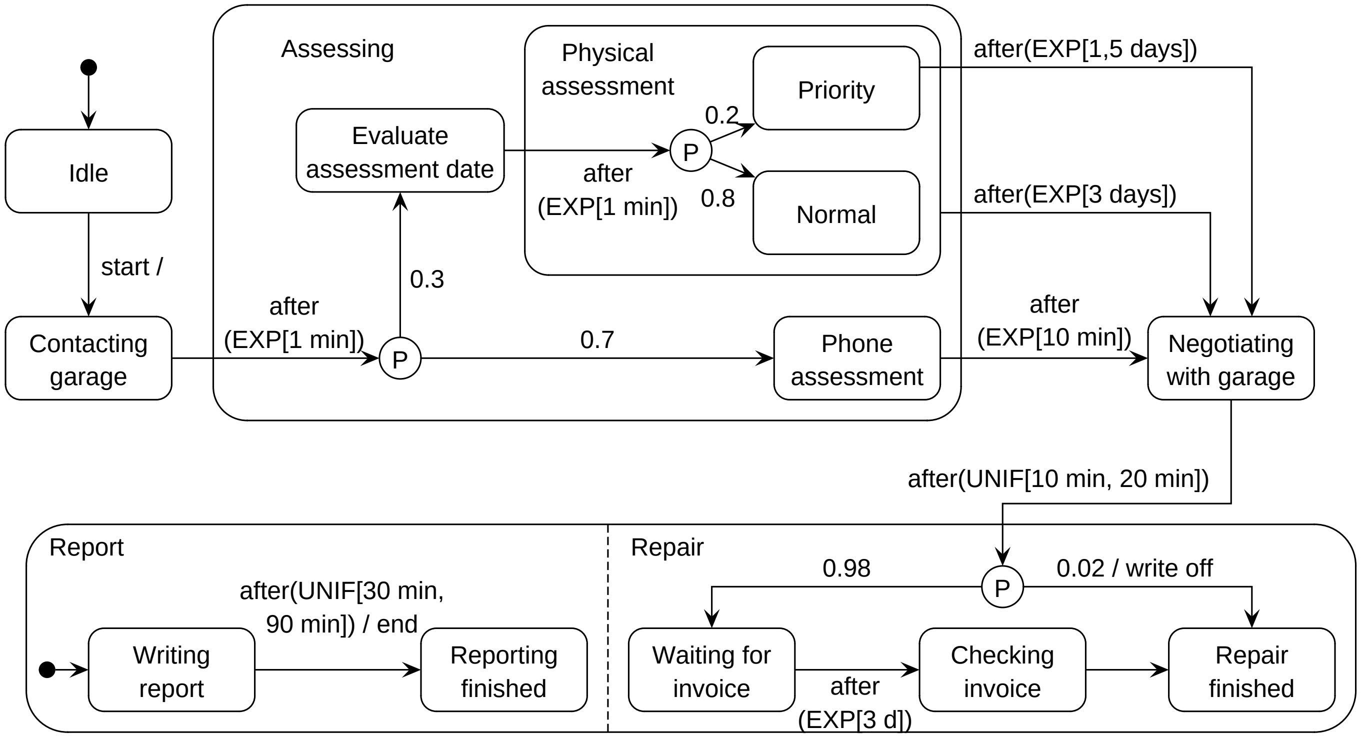
Semantics of Stocharts

Material courtesy of Joost-Pieter Katoen

$\boxed{\text{The (small) adaptations needed for StoCharts}}$

This is what's all about!

A StoChart



Assessing
Physical assessment
Priority
Normal
0.2
0.8
P
Evaluate assessment date
after (EXP[1 min])
0.3
0.7
Phone assessment
Idle
start /
Contacting garage
after (EXP[1 min])
after(EXP[1,5 days])
after(EXP[3 days])
after (EXP[10 min])
Negotiating with garage
after(UNIF[10 min, 20 min])
Report
after(UNIF[30 min, 90 min]) / end
Writing report
Reporting finished
Repair
0.98
0.02 / write off
Waiting for invoice
after (EXP[3 d])
Checking invoice
Repair finished

What is a StoChart?

A StoChart $SC = (\textit{Nodes}, \textit{Ev}, \textit{PEdges})$ with:

- A set *Nodes* of nodes structured in a tree
- A (finite) set *Ev* of events
  - pseudo-event *after*(F) denotes a random delay determined by distribution F
  - $\ldots\ldots$ the probability to wait at most d time units is $F(d)$
  - $\bot \notin \textit{Ev}$ stands for “no event”
- A (finite) set *PEdges* of probabilistic edges (in fact, hyperedges)

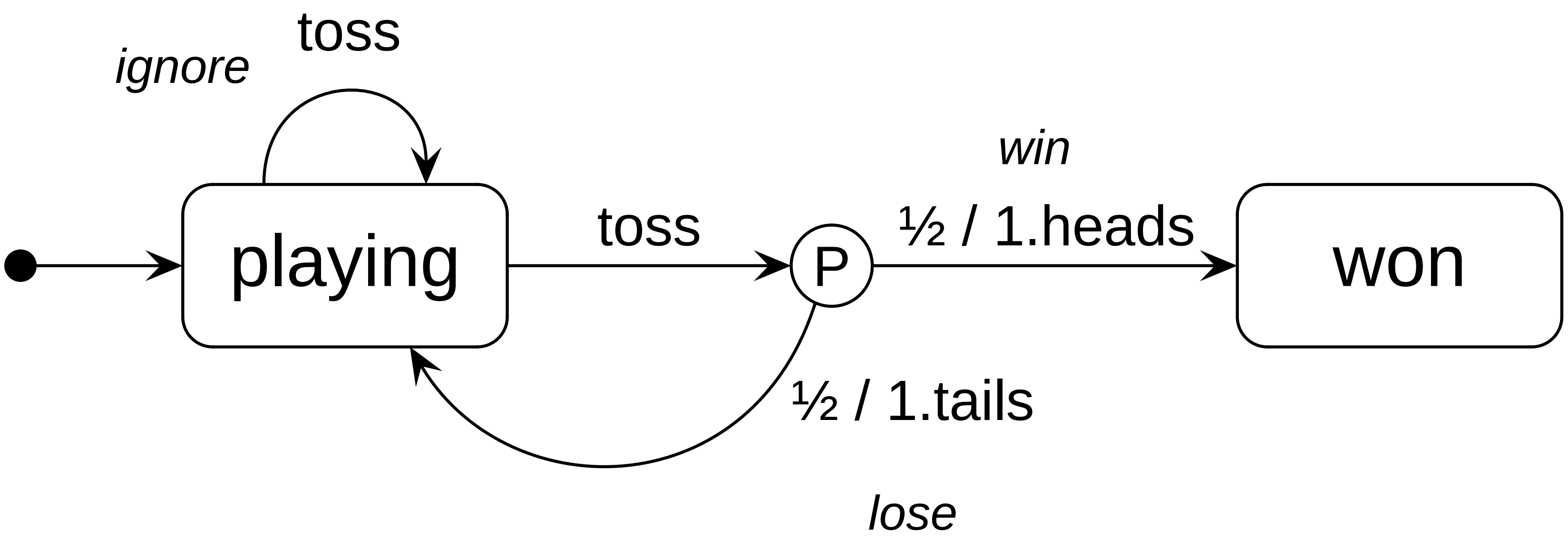
Probabilistic edges

A P-edge is a tuple (X, e, g, P), notation $X \xrightarrow{e[g]} P$, where

- X is a non-empty (source) set of nodes
- $e \in$ *Ev* is the trigger event, possibly *after*(F)
- g is a guard, i.e., a Boolean expression
- P is a function assigning probabilities to pairs (A, Y)

"if currently in X and g holds, on occurrence of e,
with probability $P(A, Y)$ target Y is selected while performing actions A"

A simple StoChart



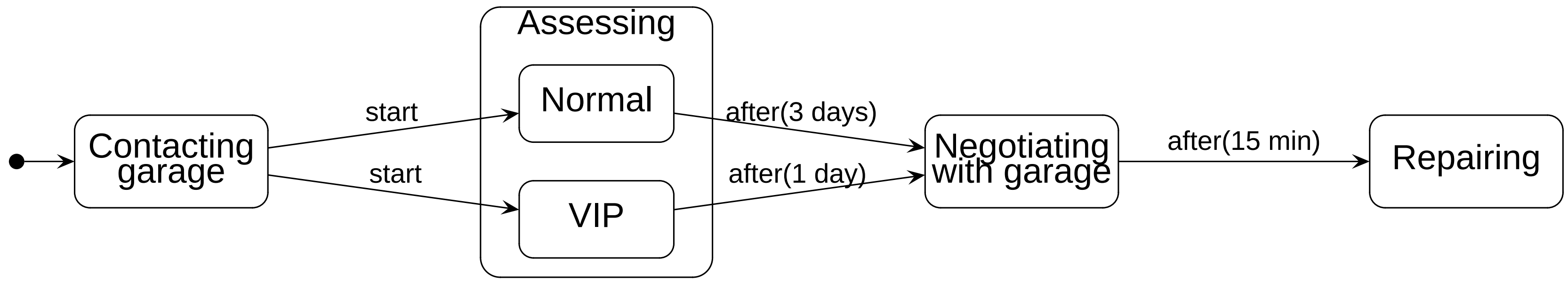
$$(\{\,\text{playing}\,\}, \text{toss}, \text{true}, P') \text{ with } P'(\varnothing, \{\,\text{playing}\,\}) = 1$$

$$(\{\,\text{playing}\,\}, \text{toss}, \text{true}, P) \text{ with } P(\{\,\text{1.heads}\,\}, \{\,\text{won}\,\}) = \tfrac{1}{2}$$

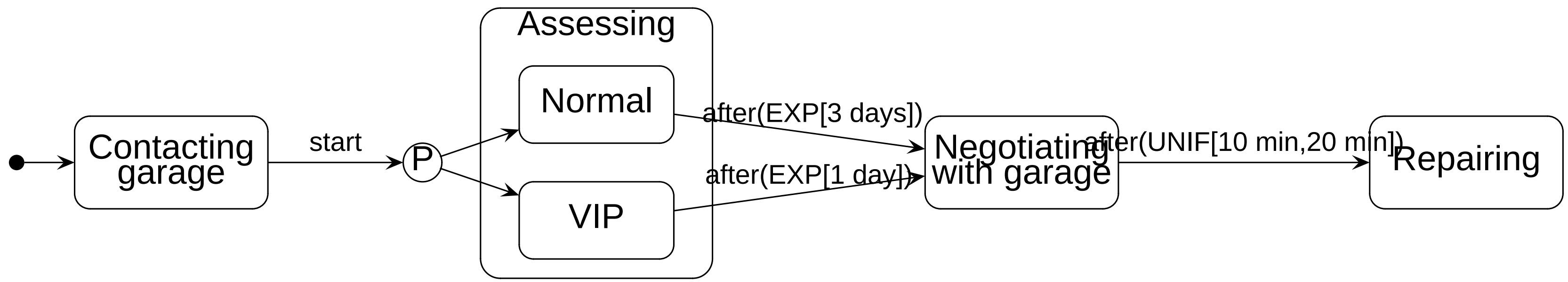
$$\text{and } P(\{\,\text{1.tails}\,\}, \{\,\text{playing}\,\}) = \tfrac{1}{2}$$

Turning a StateChart into a StoChart

A StateChart



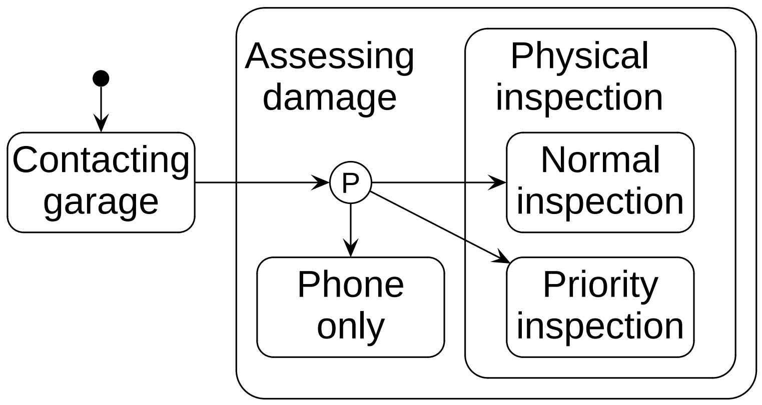
turned into a StoChart

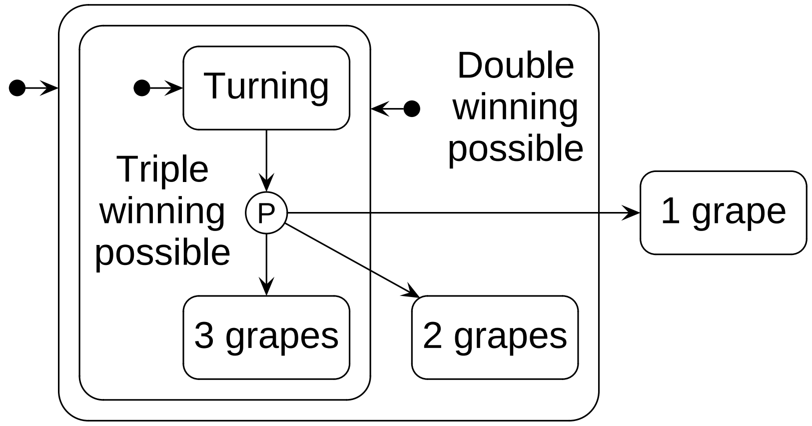


P-edges, edges and scope

(j, A, Y) is an edge of P-edge $j = (X, e, g, P)$ if $P_j(A, Y) > 0$

For simplicity: all edges of a P-edge must have the same scope





Allowed

Forbidden

Stochastic I/O automata

I/O automata extended with:

- *Timers* to model probabilistic delays
  - initialized by samples of probability distributions
  - they run backwards, all at the same pace
  - and expire when their value becomes 0

- Three types of transition relations
  - a deterministic input relation (= function)
  - a delay transition relation
  - a *probabilistic* output relation

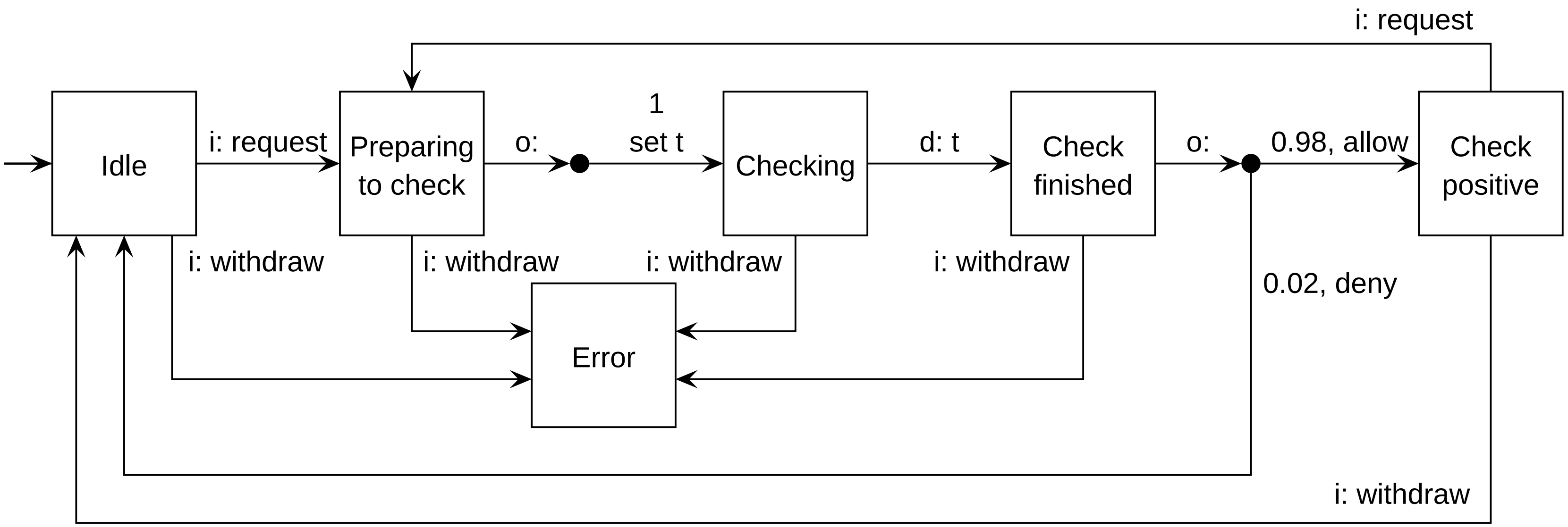
Stochastic I/O automata

A *stochastic* I/O-automaton is a tuple $(L, \ell_0, A, \mathcal{T}, I, O, \Delta)$ with

- a finite non-empty set L of locations with initial location $\ell_0 \in L$
- a set $\mathcal{T}$ of timers, such that each timer $t \in \mathcal{T}$ has a pdf F_t
- an input function $I : L \times A^{in} \to L$ satisfying
  - input-enabledness
- an output transition relation $O \subseteq L \times \mathit{Prob}(A^{out} \times 2^{\mathcal{T}} \times L)$
- a delay transition relation $\Delta \subseteq L \times \mathcal{T} \times L$

for output-compatible IOSA, composition can be easily defined

An example IOSA



Interpretation of an IOSA

- A state = current location + values of all timers (= timer valuation)
- When is a transition enabled?
  - an output transition is always enabled
  - an input transition is enabled whenever its input action is present
  - a delay transition is enabled whenever its timer has expired
- No transition enabled?
  - time may pass (no change of location) until some transition is enabled
- Taking an output transition emanating from location l:
  - nondeterministically select a probability space $\mathcal{P}$ with $(l, \mathcal{P})$ in O
  - select one of the possible targets (a, T, l') in $\mathcal{P}$ probabilistically
  - generate output a, reset all timers in T and evolve to location l'

What kind of stochastic process?

- An IOSA is in fact a *generalized semi-Markov decision process*
- Each output-deterministic IOSA can be mapped onto a GSMP
  - this is a well-studied class of stochastic processes
  - . . . . . . for which efficient discrete-event simulation algorithms exist
  - subclasses of this model are amenable to numerical solutions
    - continuous-time Markov chains (CTMCs)
    - Markov decision processes (MDPs)
    - continuous-time Markov decision processes (CTMDPs)

In most cases we obtain a stochastic process that can be analyzed!

What does a single StoChart mean?

Intuitive semantics as a transition system:

- State = one or more nodes ("current control") + the values of variables
- P-edge is enabled if guard holds in current state
- Executing a P-edge = consume event e, and
  - probabilistically select a target state and actions
  - execute actions, leave source state and switch to target state
- Principle: execute as many edges at once (without conflict)

$\Rightarrow$ this is called a *step*

Isn't this the same as before? Yes, almost! Only the probabilistic selection

What is now a step?

A step is a set of enabled edges such that:

- all edges in a step are enabled
- all edges are pairwise consistent
  - scopes are (descendants of) different children of the same AND-node
- enabled edge ed is not in step implies

  $\exists ed' \in$ step. $\;(ed$ inconsistent with ed' and *prio*$(ed') \geqslant$ *prio*$(ed))$
- a step must be maximal (wrt. set inclusion)

Isn't this the same as before? Yes, indeed!

Computing the set of steps

1. Calculate the set of *enabled* P-edges
2. Calculate all maximal, prioritized, consistent sets of P-edges thereof
3. Select nondeterministically one of them
4. Draw samples from the probability space of the P-edges
   - this results in a set of edges together forming a *step*
   - the probability of the step is simply the product of the individual edges

Isn't this the same as before? Well almost, except the last step!

From StoCharts to an IOSA

- $L = (\mathit{Conf}_1 \times 2^{\mathit{Ev}_1} \times \mathit{Val}_1) \times (\mathit{Conf}_2 \times 2^{\mathit{Ev}_2} \times \mathit{Val}_2)$
- $\ell_0 = (s_{0,1}, s_{0,2})$, where $s_{0,i} = (C_{0,i}, \varnothing, V_{0,i})$ is the initial location of SC_i
- For each P-edge with label $\mathsf{after}(F_{ij})$, $\exists$ timer $t_{ij} \in \mathcal{T}$ with cdf F_{ij}
- $A^{in} = 2^{\mathit{Ev}_1 \cup \mathit{Ev}_2} - \{ \varnothing \}$
- $A^{out} = 2^E$ with $E = \{ \mathit{send}\ j.e \in \mathit{SC}_1 \cup \mathit{SC}_2 \mid j \neq 1, 2 \}$
- $\dfrac{E \in A^{in}}{(\ell_1, \ell_2) \xrightarrow{E} (\ell_1', \ell_2')}$ with $s_j = (C_j, I_j, V_j)$ and $\ell_j' = (C_j, I_j \cup (E \cap \mathit{Ev}_j), V_j)$

The delay transition relation

$$\frac{X \subseteq C_1 \quad (X, \mathsf{after}(F_{1,j}), g, P) \in PEdges_1}{((C_1, I_1, V_1), (C_2, I_2, V_2)) \xrightarrow{t_{1,j}} ((C_1, I_1 \cup \{\mathsf{after}(F_{1,j})\}, V_1), (C_2, I_2, V_2))}$$

and symmetrically for SC_2

Output transition relation

Let $PT_i = (2^{\textsf{Edges}_i}, P_i) \in PSteps(EnP(C_i, I_i, V_i))$ for each i

Then $((C_i, I_i, V_i)_{i=1}^{2}, (A \times 2^{\mathcal{T}} \times L, P)) \in O$ with probability measure:

$$P(\{(E, T, Exec(C_{1\ldots 2}, T_{1\ldots 2}, V_{1\ldots 2}))\}) = P_1(\{T_1\}) \cdot P_2(\{T_2\})$$

where E is the set of events that are sent to the environment, and

$$T = \{t_{ij} \mid \iota_i(j) \text{ becomes enabled } \}$$

Let $P(\{(E, T, \omega)\}) = 0$ in all other cases

Put in a nutshell

- Semantics StoChart $\approx$ your favourite Statechart semantics
  - – illustrated here for the rquirements-level semantics [Eshuis & Wieringa]
  - \+ probabilistic branching and some timers for random delays
  - – . . . . . . indeed it is as simple as that!

- Formal semantics *precisely* defines the obtained stochastic process

$\Rightarrow$ This constitutes the basis for *thrustworthy* QoS analysis

- . . . . . . Applications indicate what you can do with this framework
  - – the proof of the pudding is in the eating!

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Applications

Material courtesy of David N. Jansen

Kiezen op Afstand

- KOA = Televote via WWW
- Dutch government project
- pilot (2004):
  ±8.000 voters living abroad e-voted
- final goal:
  allow all voters to e-vote on Vote Day

high availability (and performance)

in a very limited period (12 h)

Quality Goal

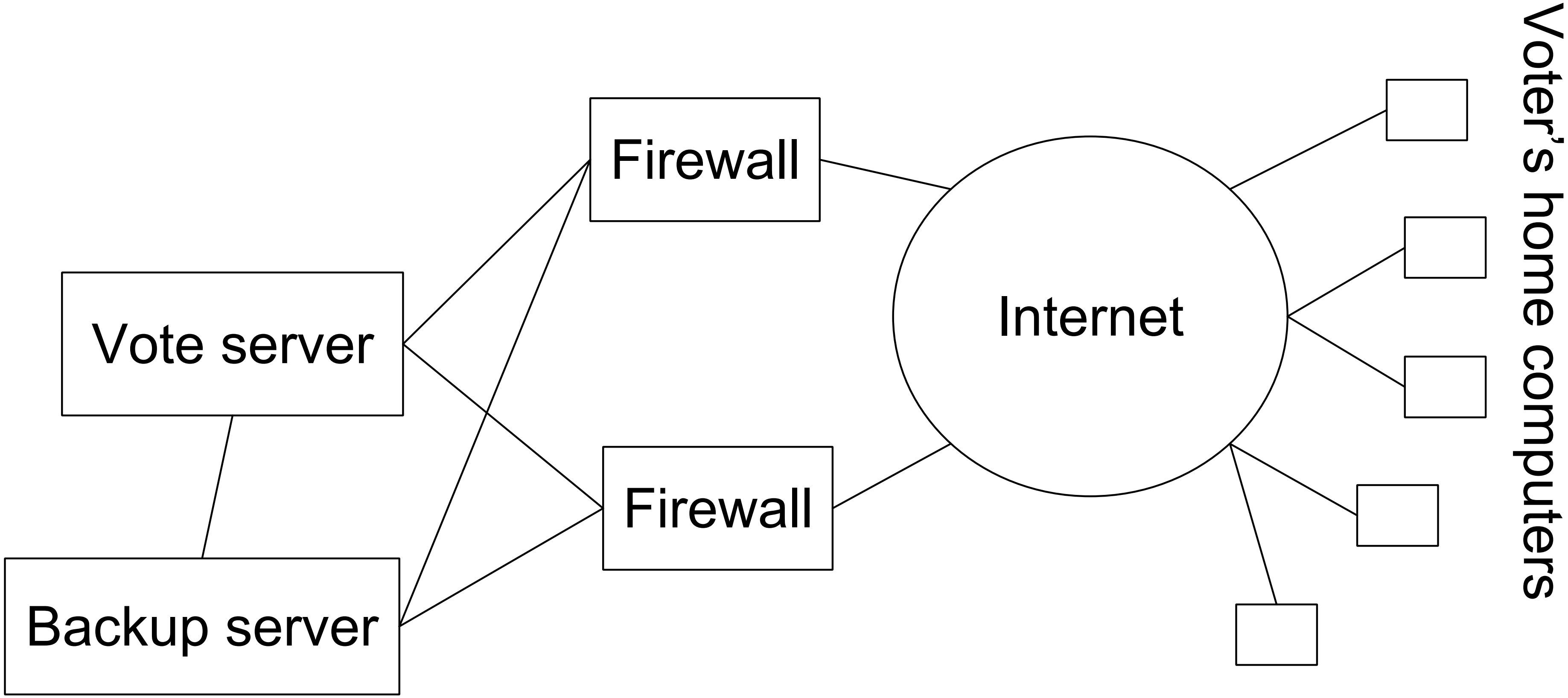
- Long downtimes are unacceptable

- Long downtime := 10 minutes
- Unacceptable := once in 10^3 votes

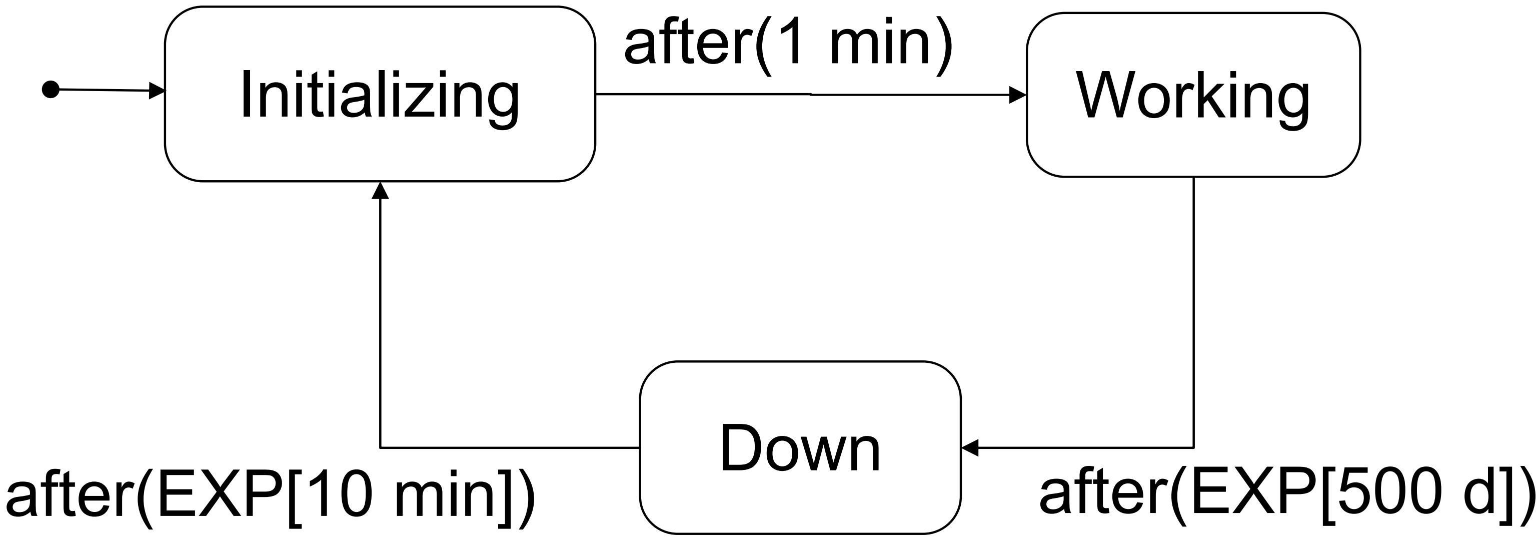
- Q: What is the probability that a televote system has an unacceptable downtime?

- A: ... using a StoChart model ...

A Televote System



Firewall model



Televote: Assignment

- Model the Vote and Backup servers

- Vote server characteristics:
  - startup time: 2 min
  - MTTF: 500 days
  - MTTR: 10 min

- Backup server characteristics:
  - startup time, MTTF and MTTR as above
  - from hot standby to full operation:
    1 min

Televote: Solution

Televote: System Analysis

- Simulated using the tool Ymer
  - statistical sampling:
    generate large number of runs
    and estimate the desired probability
  - analyzes GSMPs
  - developed by Håkan Younes at CMU

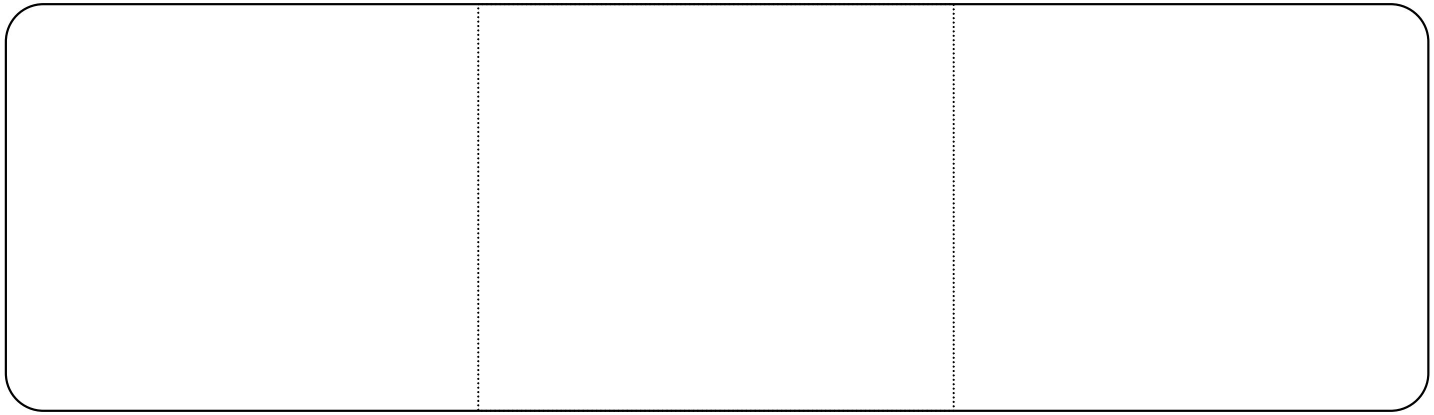
- Result: Yes!
  This Televote system is reliable enough

One-Armed Bandit

- Gambling machine
- 3 reels show fruit symbols etc.
- Some combinations incur a prize
- Prize probability prescribed by law

One-Armed Bandit: Assignment

- The 3 reels spin in parallel and (almost) independently
- Easy to model as a StoChart



- Assignment:
  draw a model of the reels

One-Armed Bandit: Solution

One-Armed Bandit: System Analysis

- Model checked using the tool Prism
  - numerical solution of the Markov decision process
  - developed by Kwiatkowska's group (Birmingham)

- Desired properties checked:
  legal requirements on win and loss

Example Properties

- In 30 games, the player loses ≤ 15 coins with probability >0.5
- In 30 games, the player wins <10 coins with probability ≥ 0.99
- In 1000 games, the probability that the automaton cannot pay out is $\leq 10^{-20}$

European Train Control System

Train Interoperability

- Interoperability:
  one railway's train runs on another railway's track
- Some interoperability is given

- Broken by different security systems

Securing Trains: Practice

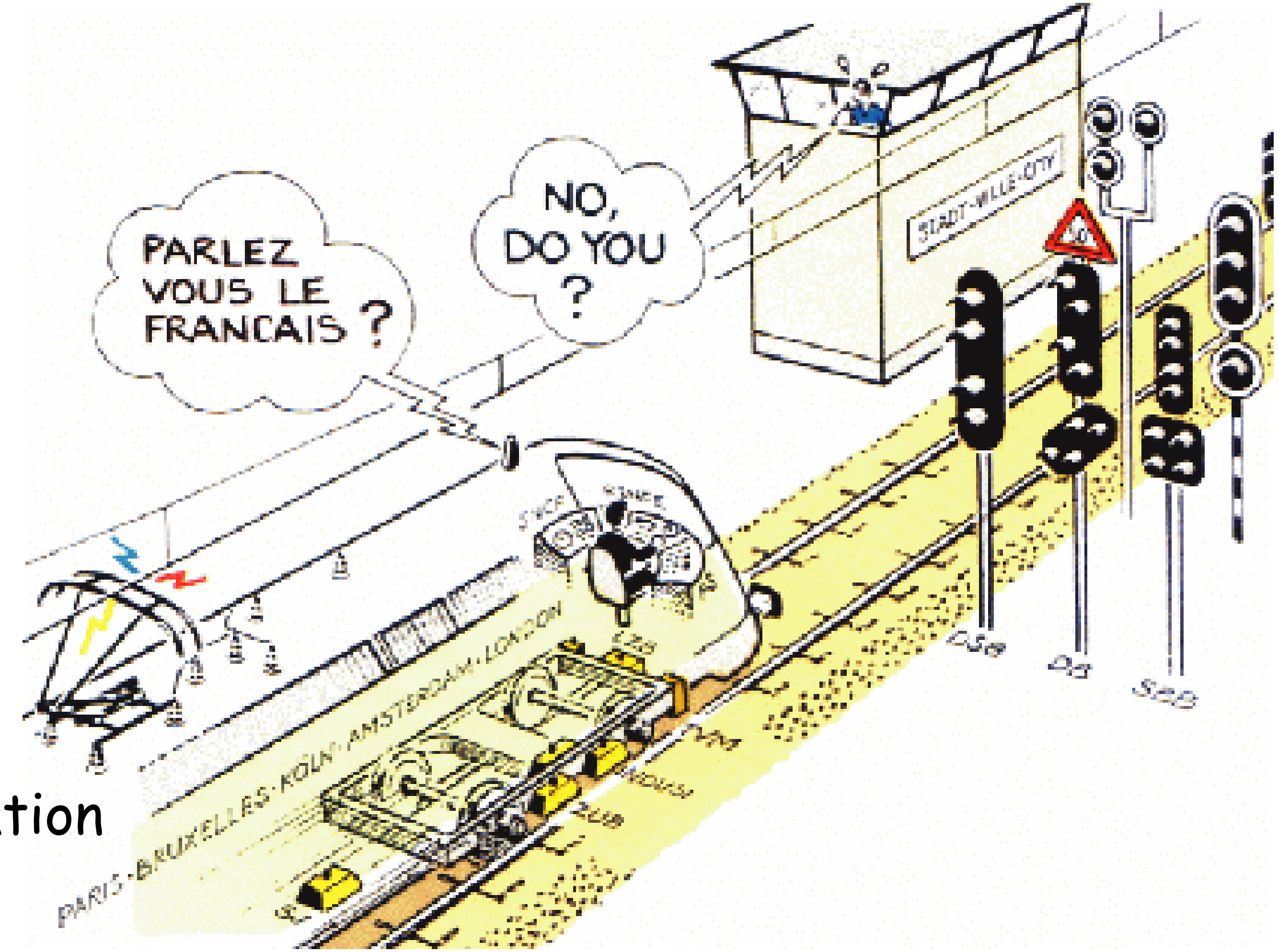
- Signals show movement authorities to the driver
- Some protection against human error
  - Indicate passage of danger points

Different national systems

- Eurobalise
  - trackside transceiver
  - transmits position, movement authorities etc.

ETCS: Next-generation trains

- Future standard for cross-European trains
- Defines train interoperability, not train internals
- Moves functionality inside train, to improve track utilisation
- Train-trackside communication via 'GSM-R'



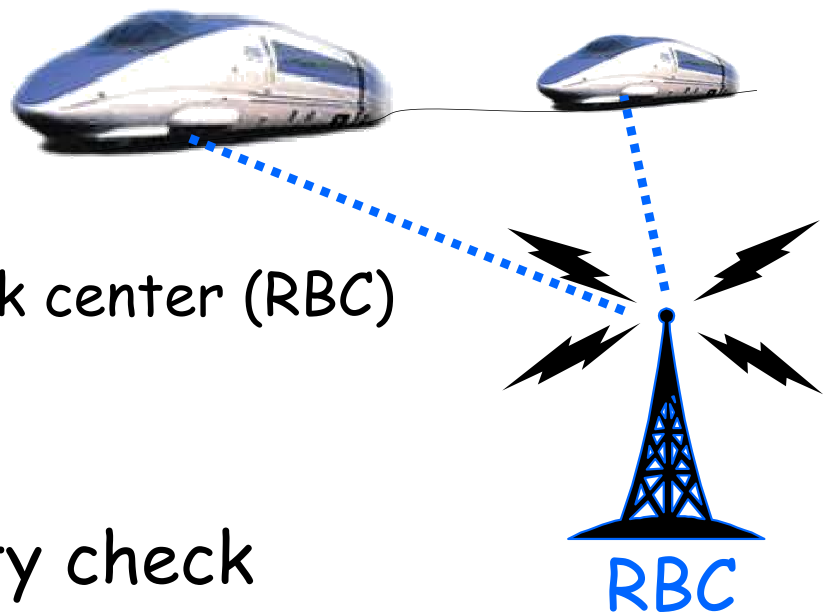
Speaking technically

- Eurobalise
  - trackside transceiver
  - transmit position and movement authorities etc.

ETCS Level 1

- GSM-R
  - a variant of GSM
  - transmit movement authorities etc.
  - communicate with trackside radio block center (RBC)

ETCS Level 2+3

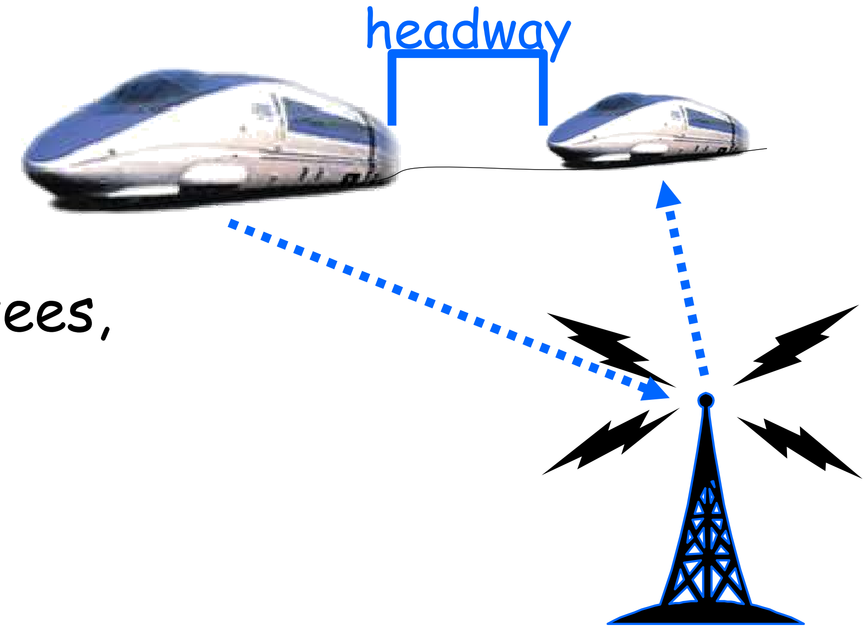


- Cab signalling and on-board integrity check
  - train internals
  - only a few aspects specified

ETCS Level 3

Is GSM-R reliable enough?

- Various standard documents detail reliability, dependability and availability requirements to be fulfilled by
  - GSM-R
  - ETCS level 1,2,3



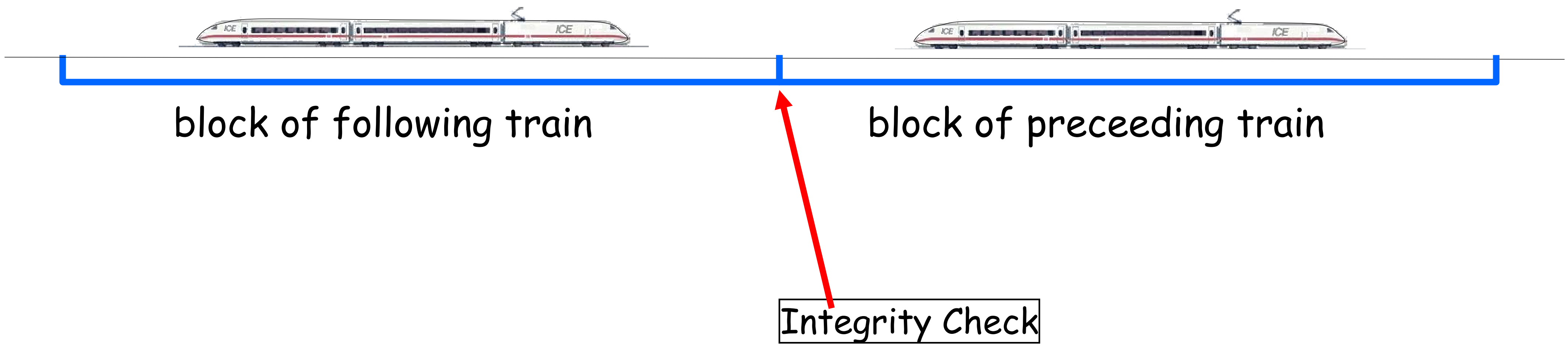
- We take the GSM-R specs as guarantees, and verify the ETCS requirements

- Level 3:
  - 'Moving block operation'
  - 'private' track area moves with train
  - train informs track-side dispatcher at regular intervals about
    - position
    - train integrity
  - dispatcher notifies following train

Why? Is expected to allow shorter headways.

ETCS Level-3:
Moving Block Operation

- Enabled by on-board integrity check
- Each fraction of the rails is freed immediately after the train has passed...
- ... and can be reserved for the next train without delay
- shorter headway thus better track utilisation



ETCS Level-3: Moving Block Operation

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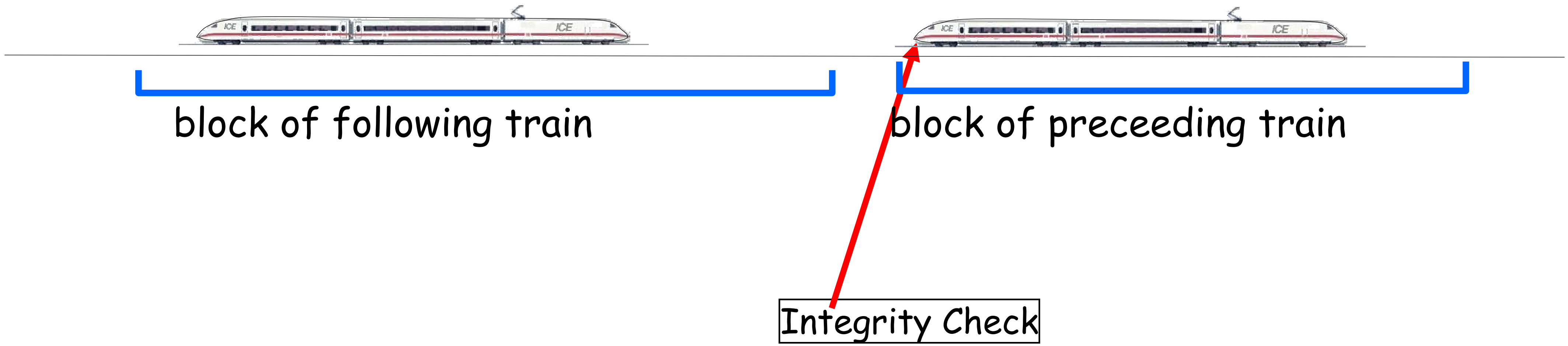


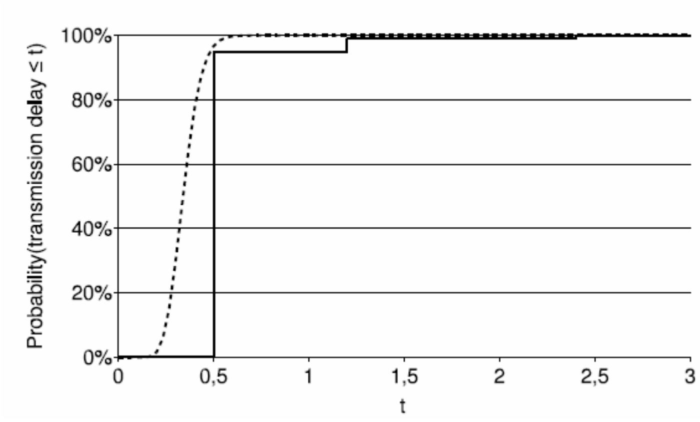
ETCS train radio reliability

- **Question:** Can GSM-R radio handle train communications?
  - fast ($\geq$ 300 km/h)
  - in dense traffic (headway $\approx$ 1 min)
  - with high reliability (99.95%)
- **Answer:** Yes

So, that's good. Let's skip the details then.

Assumptions and Guarantees

- "Design by Contract" paradigm



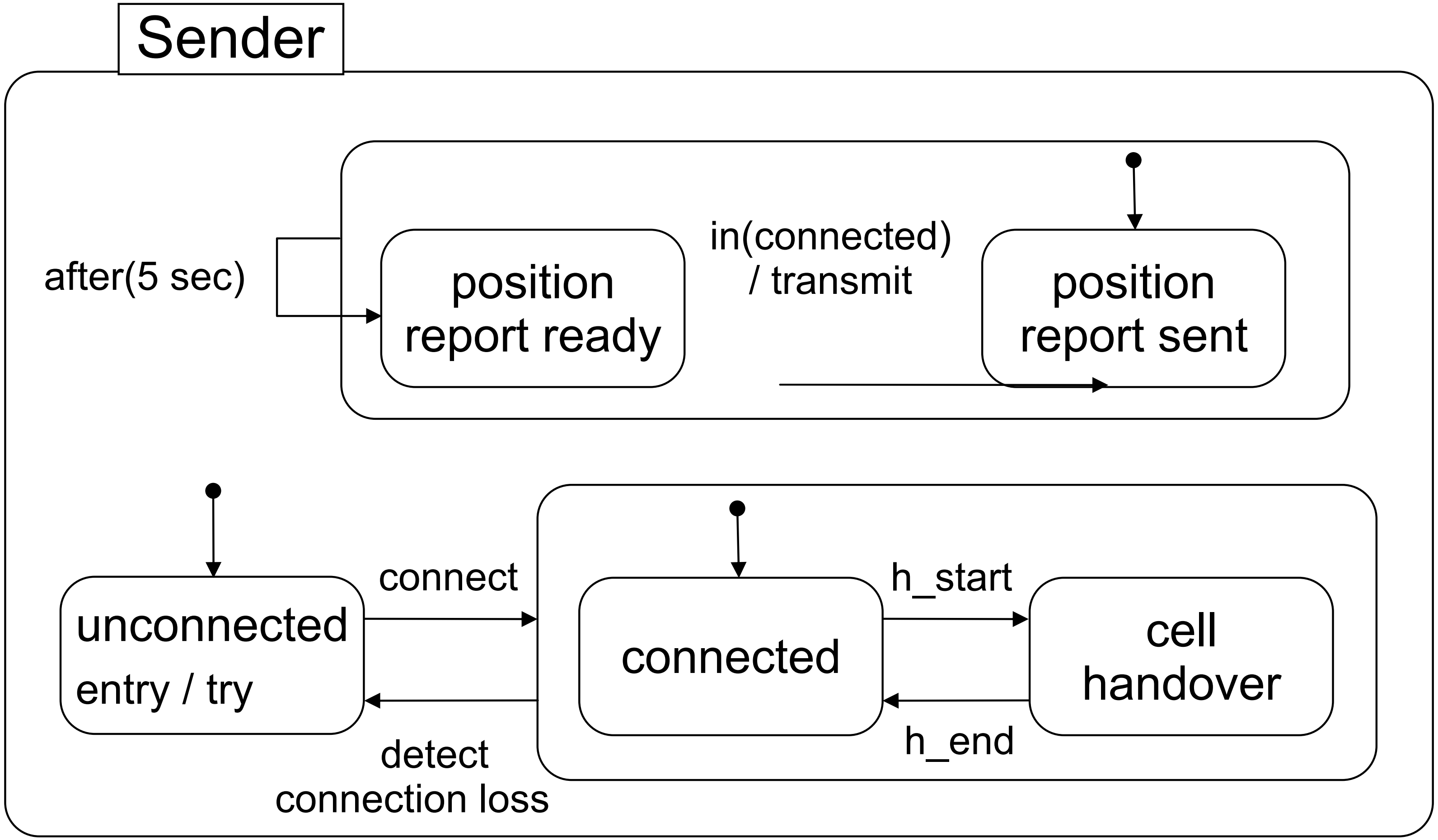
- If the environment keeps the assumptions, the system is guaranteed to fulfil its duty.

- Our assumptions: GSM-R works as specified
  - e. g. "a GSM-R connection is established within 5 sec with 95% probability."

- Our guarantees: ETCS radio is as dependable as specified

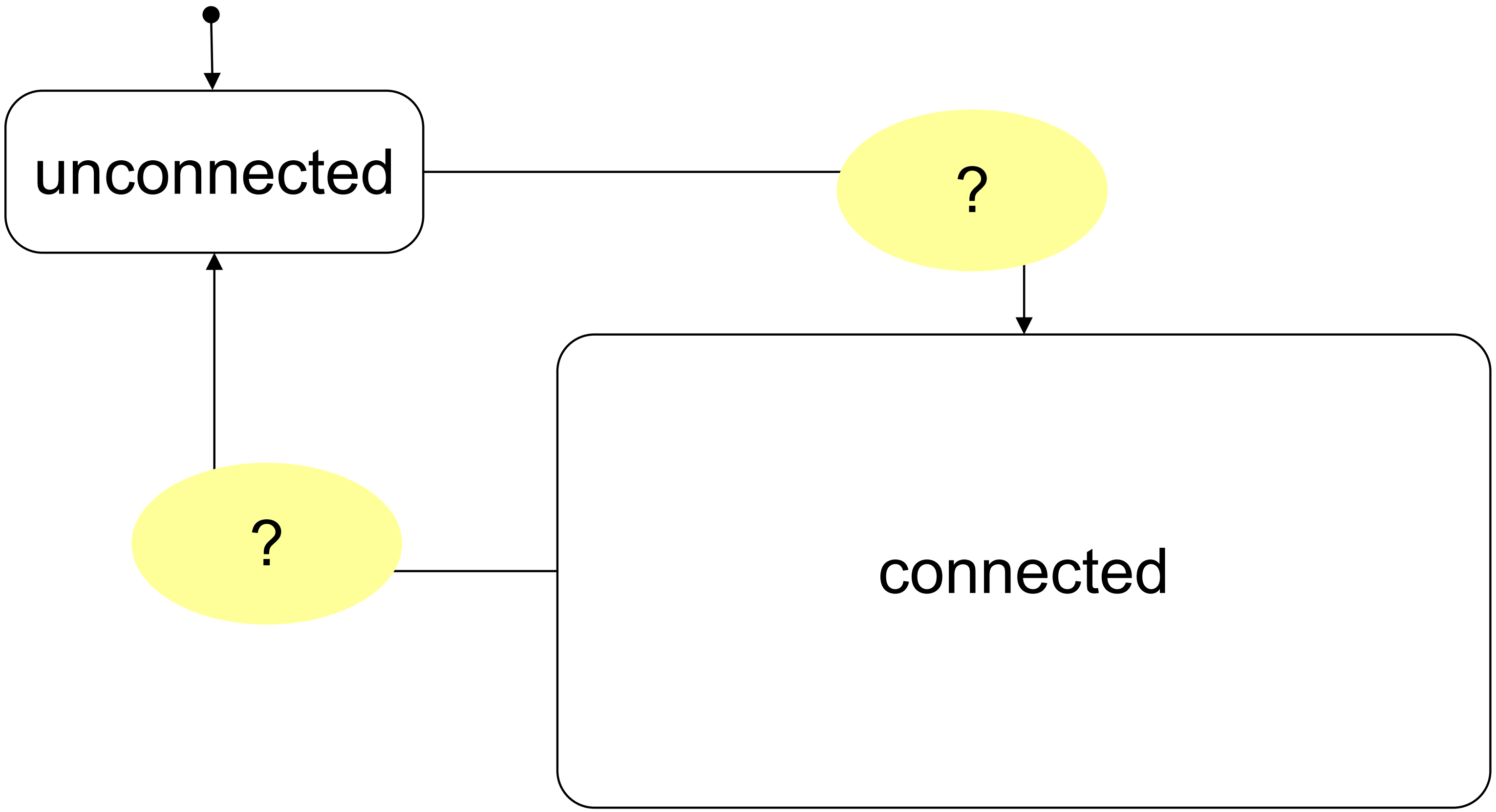
  - e. g. "the communication succeeds with 99.95% probability".

Sender Model



ETCS: Assignment

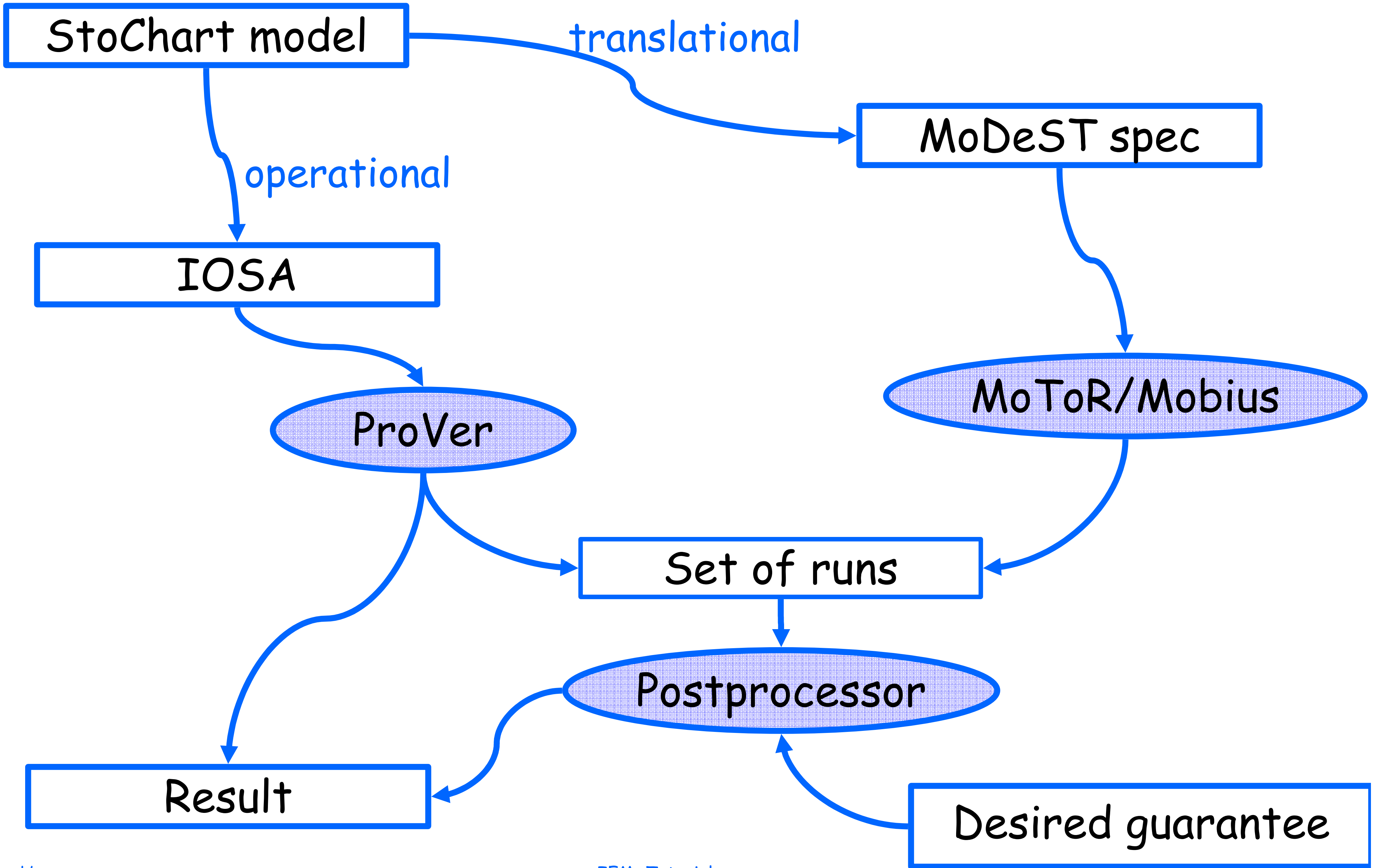
- Complete the connection timing in this transmission medium model



Overview

- Context: Train signalling
- European Train Control System Standard
- Models and Modelling
- ETCS Communication Reliability
- Experiments and Results
- Conclusion

Model Analysis

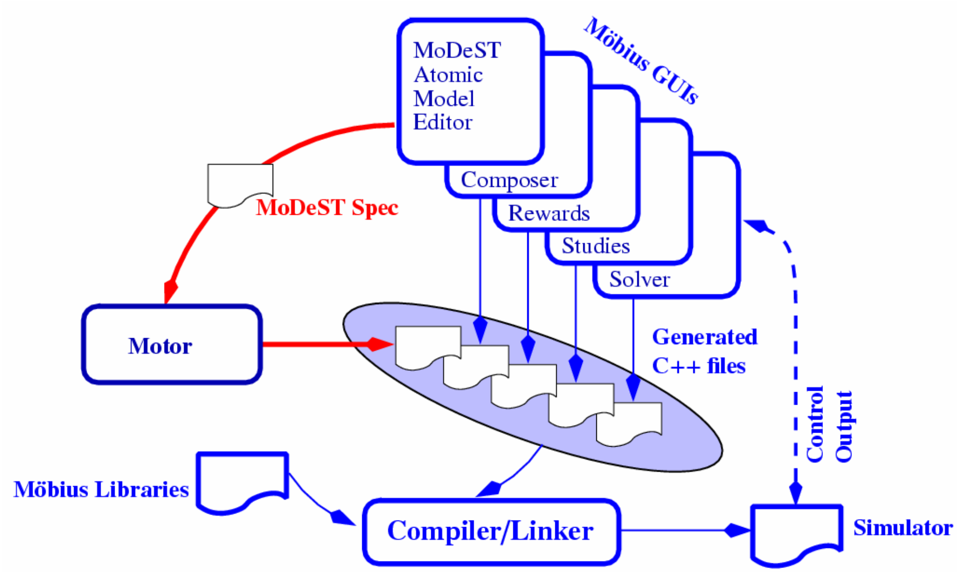


ProVer

- model checker look-alike simulation tool:
  checks whether a probabilistic property is satisfied
  - e. g.: Is the probability of a failure less than 1%?
  - Possible answer: Yes, with confidence 0.99.
- tailored to GSMPs (deterministic IOSA)
- developed at CMU by Håkan Younes

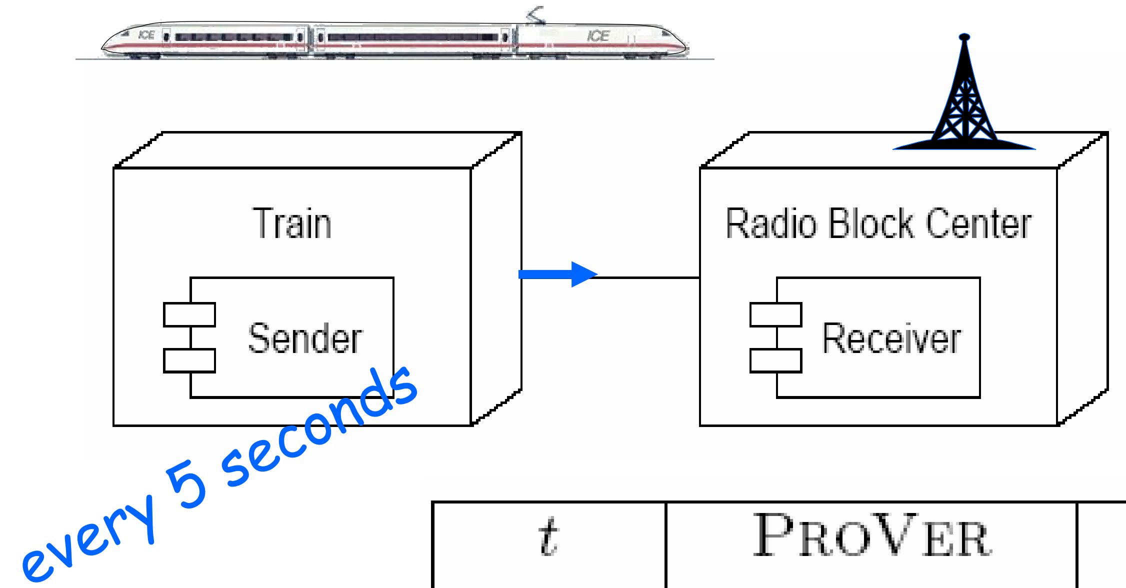
MoDeST tool support

- MoToR:
  a frontend for MoDeST developed at University of Twente
- Mobius:
  - flexible modelling and analysis environment for discrete event systems
  - developed in the PERFORM group at UIUC Urbana-Champaign
  - rooted in Petri nets, but quite component-oriented



Communication Reliability

- Is the communication reliable enough?
- Required by the spec: 99.95%

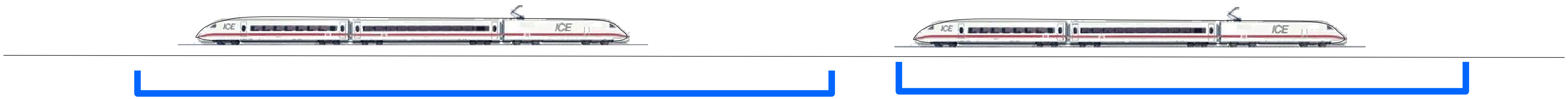


Does the next message arrive at the RBC within *t* sec?

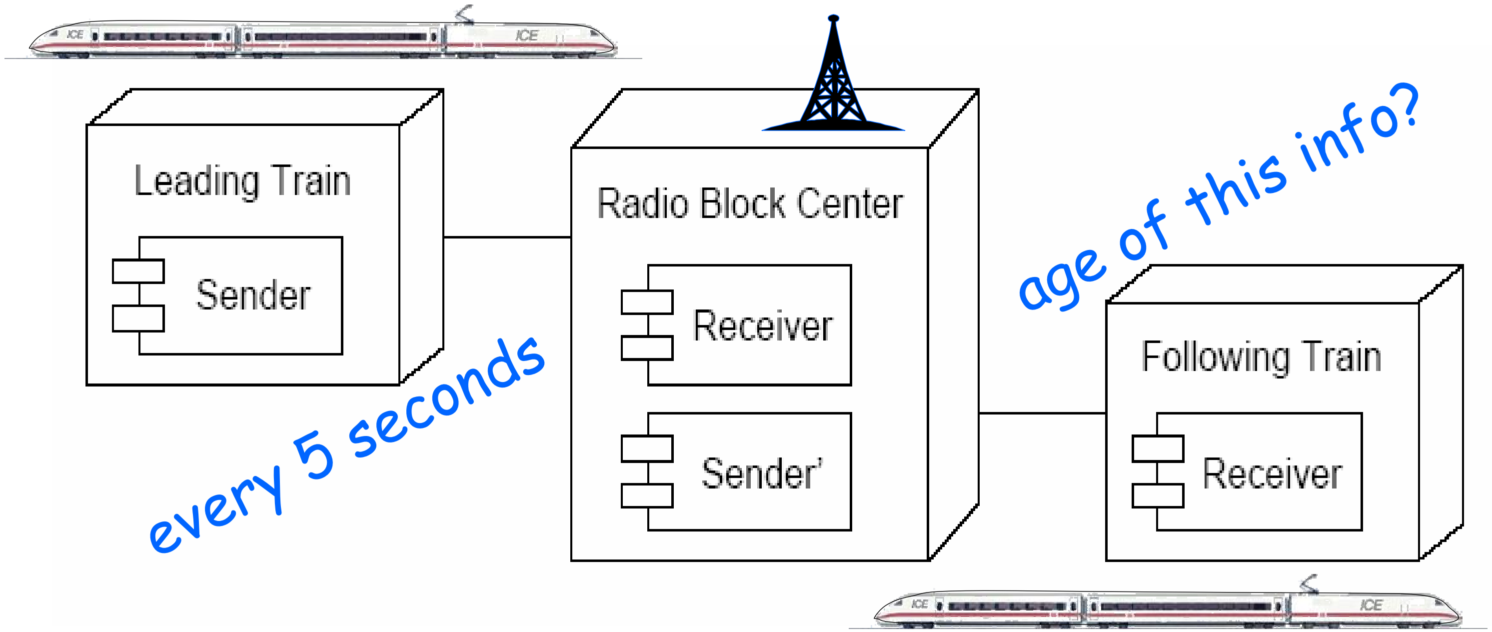
t	ProVer direct	ProVer +Postprocessor	MoDeST +Postprocesso
5 sec	0	0	0
10 sec	0.98267±9	0.98271± 6	0.9840
15 sec	0.999700±9	0.999688± 8	0.9997
20 sec	0.9999944±6	0.9999950±10	0.9999

Delayed Trains

- How often do GSM-R failures cause delays?
- Challenging scenario:
  Two trains at minimal distance
  - for a full trip (~ 1 hour)
  - at maximum speed (300 km/h)
  - with moving block operation



Delayed Trains



4 train pairs per hour

< 1 train per month delayed

max Δt	ProVer direct	ProVer +Postprocessor	MoDeST +Postprocessor
> 5 sec	1	1	1
> 10 sec	$0.9562\pm\ 9$	0.9551 ± 13	0.9338 ± 16
> 15 sec	$0.101\pm\ 2$	$0.1006\pm\ 9$	0.0784 ± 18
> 20 sec	$0.0036\pm\ 4$	$0.0041\pm\ 4$	$0.0023\pm\ 3$
> 25 sec	0.00034 ± 11	0.00029 ± 11	$0.00004\pm\ 4$
> 75 sec	0	0	0

Hawks and Doves

Simulation Games

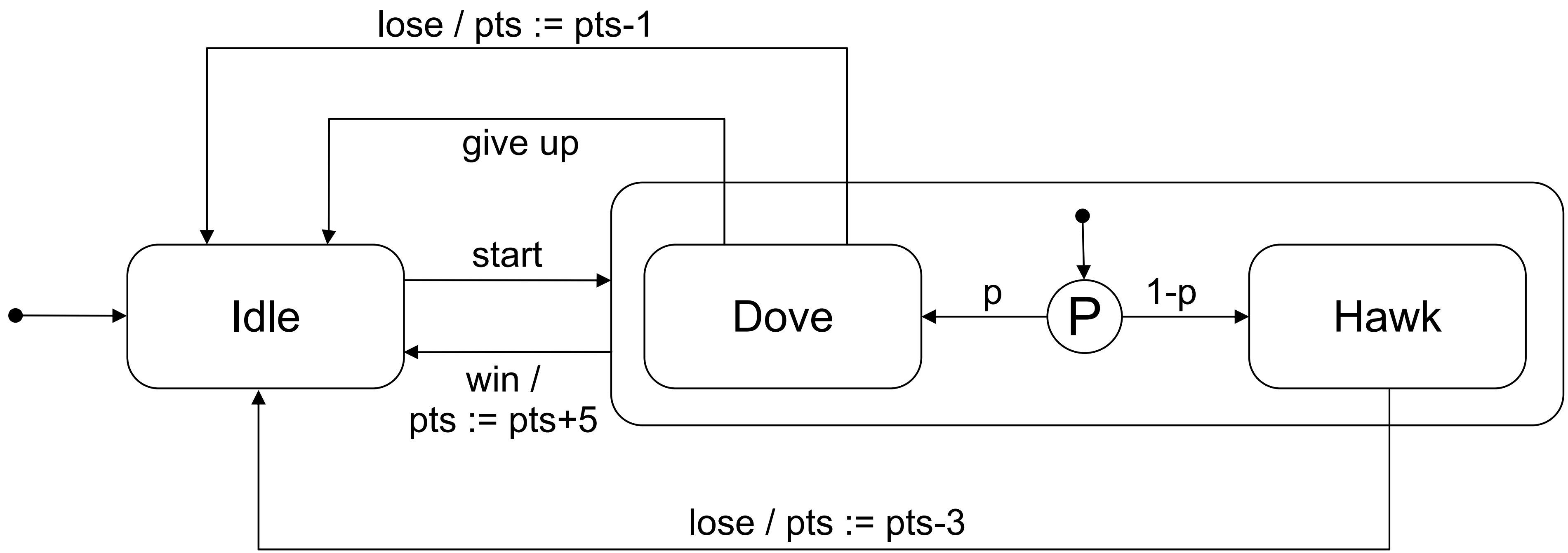
- Model used in biology
- conflicts between animals
  - fight for some advantage (e. g. food, territory)
  - measured in points
- Strategies considered:
  - Hawk: fight forcefully,
    don't give up unless severely injured
  - Dove: fight with limited effort
    or give up before getting injured

System Model

- Arbiter selects who is to fight nondeterministically
- Three individuals select hawk/dove strategy probabilistically
- Arbiter decides who wins

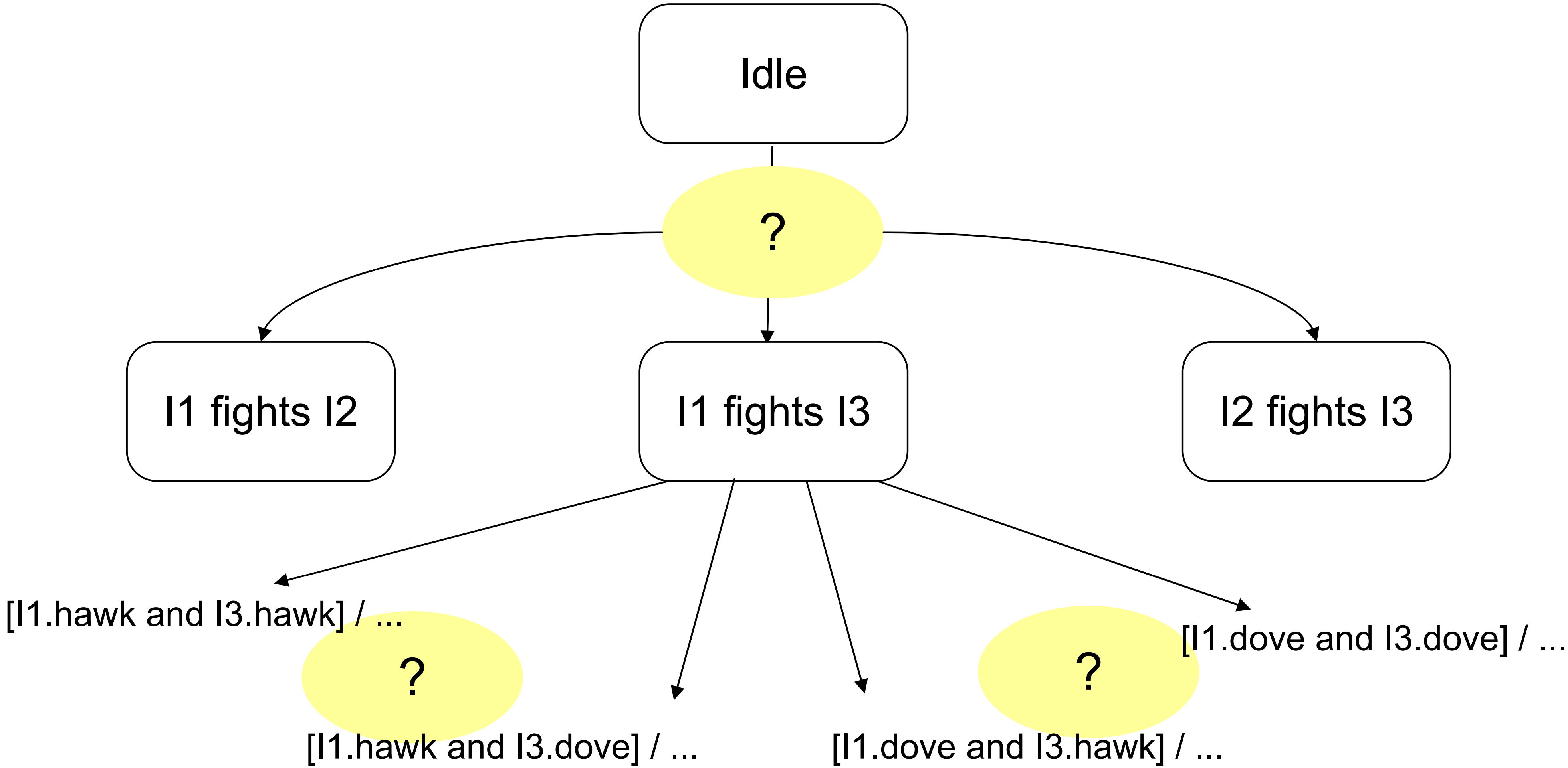
Individual StoChart

- p = probability to choose dove strategy



Hawks and Doves: Assignment

- Complete the Arbiter StoChart



Hawks and Doves: Solution

Hawk and Doves: Analysis

- Model checked using the tool Prism
- Situations checked:
  - 3 peaceful animals
  - 3 aggressive animals
  - 1 aggressive and 2 peaceful animals

Hawks and Doves: Analysis

- The probability to die is < 1%
  - "to die" = "pts < 1"
  - 3 peaceful: yes
  - 3 aggressive: no
- The probability to earn 20 points in 100 steps is < 75%.
  - 3 peaceful: no
  - 3 aggressive: yes
  - mixed: the hawk has an advantage

Overview

- Introduction to QoS modeling and analysis
- Introduction to Statecharts
- StoCharts
  - Introduction
  - Semantics
  - Applications
- Conclusions and future outlook

Conclusions

Conclusion

- What did you learn?
  - Stochastic modelling principles
  - Statechart principles
- StoCharts
  - Principles
  - Applications