

### 3. Behavioural Modelling

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RAMDE – Requirements and Model-driven Engineering 2021/22

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<https://cister-labs.github.io/ramde2122>

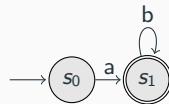
# Overview

## So far

- Models and properties for **structures**: boolean and 1st order logic, ...
- Useful, e.g., for UML class diagrams

## Next

- Look at UML **behaviour** diagrams
- Use a domain with a **precise semantics**
  - Non-deterministic finite **automata** (NFA)
  - Simple language for **processes**
  - Encode processes  $\rightarrow$  NFA
  - Equivalence of processes



# What are formal methods?

Formal methods are **techniques** to  
model **complex systems** using  
**rigorous mathematical models**

## Specification

Define part of the system  
using a modelling  
language

## Verification

Prove properties.  
Show correctness.  
Find bugs.

## Implementation

Generate correct code.

All formal models are wrong

All formal models are wrong  
... but some of them are usefull!

- High-level overview or requirements and associated processes
- Mathematical Preliminaries
  - Basic mathematical notations
  - Set theory
  - Propositional Logic
  - First Order Logic
  - The Z3 automatic theorem prover
- Behavioural modelling
  - Single component
    - State diagrams and Flow charts
    - Formal modelling: Automata, Process Algebra in mCRL2
  - Many components
    - Communication diagrams and Sequence diagrams
    - Formal modelling: Process algebra with interactions
  - Equivalences
  - Verification

# UML behaviour diagrams

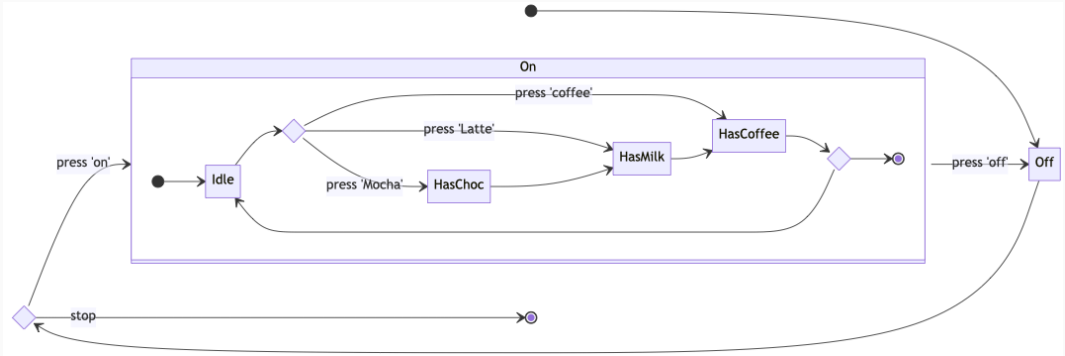
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Describe the **state** of a component, what **actions** it can do, and how it **evolves** during its life cycle.

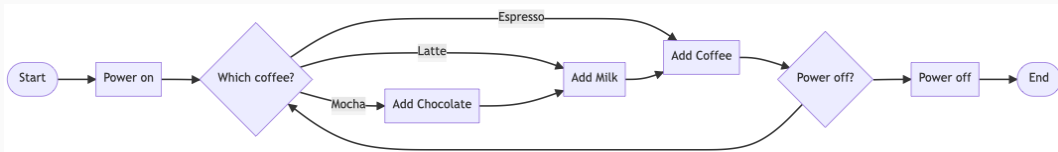
- **State Diagram** focus on states
- **Flowchart** focus on actions (also known as *activity diagrams*)



# Coffee State Diagram



# Coffee Flowchart



Used symbols: *processes, decisions, and start/end*

Other symbols include: data (or input/output), documents, connectors, comments

## **Automata – Basic definitions**

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# Sequential and Reactive systems

## Sequential systems

Meaning is defined by the results of finite computations

We start here. . .

## Reactive systems

Meaning is determined by **interaction** and **mobility** of **non-terminating** processes, evolving **concurrently**

then we go reactive

# Non-Deterministic Finite Automata (NFA)

## Definition

A NFA over a set  $N$  of **names** is a tuple  $\langle S, I, \downarrow, N, \longrightarrow \rangle$  where

- $S = \{s_0, s_1, s_2, \dots\}$  is a set of **states**
- $I \subseteq S$  is the set of **initial** states
- $\downarrow \subseteq S$  is the set of terminating or **final** states

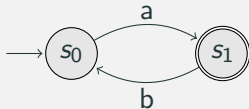
$$\downarrow s \equiv s \in \downarrow$$

- $\longrightarrow \subseteq S \times N \times S$  is the **transition** relation, often given as an  $N$ -indexed family of binary relations

$$s \xrightarrow{a} s' \equiv \langle s, a, s' \rangle \in \longrightarrow$$

# Example

## Example of an automaton

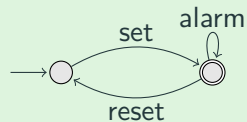
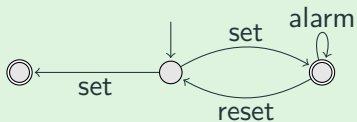


$s_0$  is an initial state

$s_1$  is a final state

(Formalise this automata)

**Ex. 3.1:** Formalise these automata as  $\langle S, I, \downarrow, N, \longrightarrow \rangle$



## A note on Individual Exercises

- 10% of the final mark
- focus on effort – doing badly is better than not doing
- submission: a PDF by email to the teacher who provided the exercises; here [pro@isep.ipp.pt](mailto:pro@isep.ipp.pt).

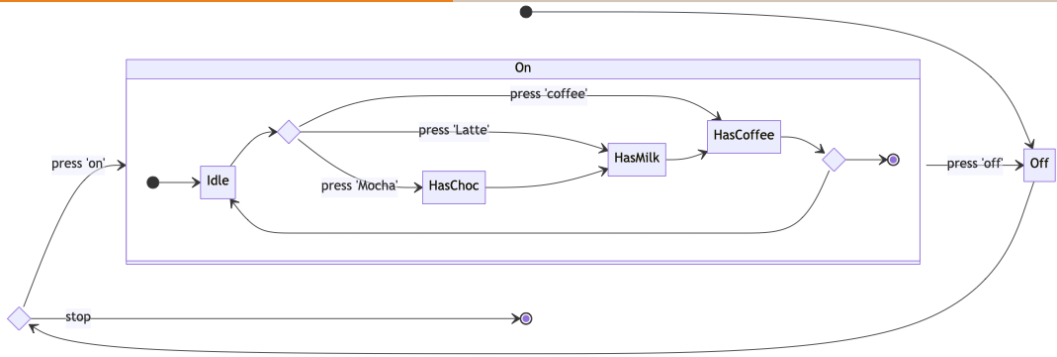
### Deadlines

Exercises presented in a given week must be submitted by the end of the following week, Sunday @ 23h59.

Website/Teams will be kept up-to-date with ongoing open submissions.



# Exercise



## Ex. 3.2: Draw LTS

(suggestion: by hand on a paper, and take a photo of it.)

# Labelled Transition System

More generally, a NFA  $\langle S, I, \downarrow, N, \longrightarrow \rangle$  is a **labelled transition system** (LTS)  $\langle S, N, \longrightarrow \rangle$ , where each state  $s \in S$  determines a **system** over all states reachable from  $s$  and the corresponding restriction of  $\longrightarrow$ .

## LTS classification

- deterministic
- non deterministic
- finite
- finitely branching
- image finite
- ...

## Definition

The **reachability relation**,  $\longrightarrow^* \subseteq S \times N^* \times S$ , is defined inductively

- $s \xrightarrow{\epsilon}^* s$  for each  $s \in S$ , where  $\epsilon \in N^*$  denotes the empty **word**;
- if  $s \xrightarrow{a} s''$  and  $s'' \xrightarrow{\sigma}^* s'$  then  $s \xrightarrow{a\sigma}^* s'$ , for  $a \in N, \sigma \in N^*$

## Reachable state

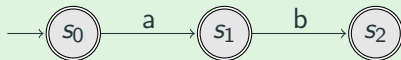
$t \in S$  is **reachable** from  $s \in S$  iff there is a **word**  $\sigma \in N^*$  st  $s \xrightarrow{\sigma}^* t$

## Language

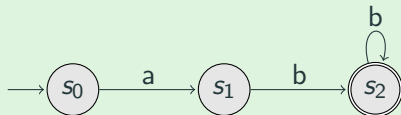
A word  $\sigma$  is in the language  $L_A$  of an automata  $A = \langle S, I, \downarrow, N, \longrightarrow \rangle$   
iff  
there are states  $s \in I, s' \in \downarrow$  such that  $s \xrightarrow{\sigma^*} s'$ .

# Exercises

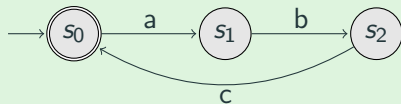
Ex. 3.3: What is the language of this automata?



Ex. 3.4: What is the language of this automata?



Ex. 3.5: What is the language of this automata?



### Regular Expressions – syntax

- $w_1 w_2$ : word  $w_1$  followed by word  $w_2$
- $w_1 + w_2$ : word  $w_1$  or word  $w_2$
- $a^*$ : 0 or more  $a$ 's
- $a^+$ : 1 or more  $a$ 's
- $\epsilon$ : empty word

### Examples

- $ab + c$ : ( $a$  followed by  $b$ ) or  $c$
- $(ab)^* b$ :  $b$  or  $abb$  or  $ababb$  or ...
- $c((ab)^* b)^+$ :  $cb$  or  $cabb$  or  $cababb$  or ...

## Extra: Regular Expressions

### Regular Expressions – syntax

- $w_1 w_2$ : word  $w_1$  followed by word  $w_2$
- $w_1 + w_2$ : word  $w_1$  or word  $w_2$
- $a^*$ : 0 or more  $a$ 's
- $a^+$ : 1 or more  $a$ 's
- $\epsilon$ : empty word

### Examples

- $ab + c$ : ( $a$  followed by  $b$ ) or  $c$
- $(ab)^* b$ :  $b$  or  $abb$  or  $ababb$  or ...
- $c((ab)^* b)^+$ :  $cb$  or  $cabb$  or  $cababb$  or ...

### NFA vs. Reg. Expr.

Word  $w$  expressible by a NFA  $\Leftrightarrow w$  expressible by a Reg. Expr.

# Process algebra

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## Sequential CCS - Syntax

$$\mathcal{P} \ni P, Q ::= K \mid \alpha.P \mid P + Q \mid \mathbf{0} \mid P[f] \mid P \setminus L \mid P \mid Q$$

where

- $\alpha \in N \cup \{\tau\}$  is an **action**
- $K$  is a collection of **process** names or process constants
- $I$  is an indexing set
- $L \subseteq N$  is a set of **labels**
- $f$  is a function that **renames** actions s.t.  $f(\tau) = \tau$
- **notation:**

$$[f] = [a_1 \mapsto b_1, \dots, a_n \mapsto b_n]$$

## Syntax

$$\mathcal{P} \ni P, Q ::= K \mid \alpha.P \mid P + Q \mid \mathbf{0} \mid P[f] \mid P \setminus L \mid P \mid Q$$

### Ex. 3.6: Which are NOT syntactically correct? Why?

$$a.b.A + B \quad (1)$$

$$(a.\mathbf{0} + b.A) \setminus \{a, b, c\} \quad (2)$$

$$(a.\mathbf{0} + b.A) \setminus \{a, \tau\} \quad (3)$$

$$a.B + [b \mapsto a] \quad (4)$$

$$\tau.\tau.B + \mathbf{0} \quad (5)$$

$$a.(a + b).A \quad (6)$$

$$(a.B + b.B)[a \mapsto a, \tau \mapsto b] \quad (7)$$

$$(a.B + \tau.B)[b \mapsto a, a \mapsto a] \quad (8)$$

$$(a.b.A + b.\mathbf{0}).B \quad (9)$$

$$(a.b.A + b.\mathbf{0}) + B \quad (10)$$

# CCS semantics - building a NFA

$$\begin{array}{c} \text{(act)} \\ \hline \alpha.P \xrightarrow{\alpha} P \end{array} \quad \begin{array}{c} \text{(sum-1)} \\ \hline \frac{P_1 \xrightarrow{\alpha} P'_1}{P_1 + P_2 \xrightarrow{\alpha} P'_1} \end{array} \quad \begin{array}{c} \text{(sum-2)} \\ \hline \frac{P_2 \xrightarrow{\alpha} P'_2}{P_1 + P_2 \xrightarrow{\alpha} P'_2} \end{array}$$
  
$$\begin{array}{c} \text{(res)} \\ \hline \frac{P \xrightarrow{\alpha} P'}{P \setminus L \xrightarrow{\alpha} P' \setminus L} \quad \alpha \notin L \end{array} \quad \begin{array}{c} \text{(rel)} \\ \hline \frac{P \xrightarrow{\alpha} P'}{P[f] \xrightarrow{f(\alpha)} P'[f]} \end{array}$$

- **Initial states:** the process being translated
- **Final states:** all states are final
- **Language:** possible sequence of actions of a process

## CCS semantics - building a NFA

$$\begin{array}{c} \text{(act)} \\ \hline \alpha.P \xrightarrow{\alpha} P \end{array} \quad \begin{array}{c} \text{(sum-1)} \\ \hline \frac{P_1 \xrightarrow{\alpha} P'_1}{P_1 + P_2 \xrightarrow{\alpha} P'_1} \end{array} \quad \begin{array}{c} \text{(sum-2)} \\ \hline \frac{P_2 \xrightarrow{\alpha} P'_2}{P_1 + P_2 \xrightarrow{\alpha} P'_2} \end{array}$$
  
$$\begin{array}{c} \text{(res)} \\ \hline \frac{P \xrightarrow{\alpha} P'}{P \setminus L \xrightarrow{\alpha} P' \setminus L} \quad \alpha \notin L \end{array} \quad \begin{array}{c} \text{(rel)} \\ \hline \frac{P \xrightarrow{\alpha} P'}{P[f] \xrightarrow{f(\alpha)} P'[f]} \end{array}$$

**Ex. 3.7: Build a derivation tree to prove the transitions below**

1.  $(a.A + b.B) \xrightarrow{b} B$
2.  $(a.b.A + (b.a.B + c.a.C)) \xrightarrow{b} a.B$
3.  $((a.B + b.A)[a \mapsto c]) \setminus \{a, b\} \xrightarrow{c} B$

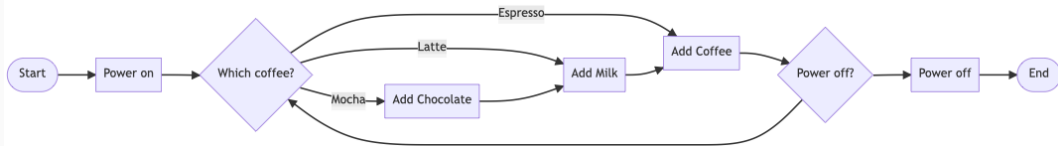
### Ex. 3.8: Draw the automata

$$CM = \text{coin.coffee}.CM$$
$$CS = \text{pub.}(\text{coin.coffee}.CS + \text{coin.tea}.CS)$$

### Ex. 3.9: What is the language of this process?

$$A = \text{goLeft}.A + \text{goRight}.B$$
$$B = \text{rest}.\mathbf{0}$$

# Exercise



**Ex. 3.10: Write the process of the flowchart above**

$P = \text{powerOn}.Q$

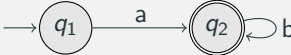
$Q = \text{selMocha.addChocolate}.Mk + \text{selLatte}.Mk + \dots$

$Mk = \text{addMilk} \dots$

# Concurrent Process algebra

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## Recall

1. Non-deterministic Finite Automata: 
2. (Sequential) Process algebra:  $P = a.Q$      $Q = b.Q$
3. Meaning of (2) using (1)

## Still missing

- **Interaction** between processes
- *Interaction diagrams* vs. *interacting processes*
- Enrich (2) and (3)



## CCS - Updated Syntax

$$\mathcal{P} \ni P, Q ::= K \mid \alpha.P \mid P + Q \mid \mathbf{0} \mid P[f] \mid P \setminus L \mid P|Q$$

where

- $\alpha \in N \cup \overline{N} \cup \{\tau\}$  is an action
- $K$  is a collection of process names or process constants
- $I$  is an indexing set
- $L \subseteq N$  is a set of labels
- $f$  is a function that renames actions s.t.  $f(\tau) = \tau$  and  $f(\overline{a}) = \overline{f(a)}$
- notation:

$$[f] = [a_1 \mapsto b_1, \dots, a_n \mapsto b_n] \quad \text{where } a_i, b_i \in N \cup \{\tau\}$$

## Syntax

$$\mathcal{P} \ni P, Q ::= K \mid \alpha.P \mid P + Q \mid \mathbf{0} \mid P[f] \mid P \setminus L \mid P|Q$$

### Ex. 3.11: Which are syntactically correct?

$$a.\bar{b}.A + B \quad (11)$$

$$(a.\mathbf{0} + \bar{a}.A) \setminus \{\bar{a}, b\} \quad (12)$$

$$(a.\mathbf{0} + \bar{a}.A) \setminus \{a, \tau\} \quad (13)$$

$$(a.\mathbf{0} + \bar{\tau}.A) \setminus \{a\} \quad (14)$$

$$\tau.\tau.B + \bar{a}.\mathbf{0} \quad (15)$$

$$(\mathbf{0}|\mathbf{0}) + \mathbf{0} \quad (16)$$

$$(a.B + b.B)[a \mapsto a, \tau \mapsto b] \quad (17)$$

$$(a.B + \tau.B)[b \mapsto a, b \mapsto a] \quad (18)$$

$$(a.B + b.B)[a \mapsto b, b \mapsto \bar{a}] \quad (19)$$

$$(a.b.A + \bar{a}.\mathbf{0})|B \quad (20)$$

$$(a.b.A + \bar{a}.\mathbf{0}).B \quad (21)$$

$$(a.b.A + \bar{a}.\mathbf{0}) + B \quad (22)$$

# CCS semantics - building an NFA

$$\frac{(\text{act})}{\alpha.P \xrightarrow{\alpha} P}$$

$$\frac{(\text{sum-1}) \quad P_1 \xrightarrow{\alpha} P'_1}{P_1 + P_2 \xrightarrow{\alpha} P'_1}$$

$$\frac{(\text{sum-2}) \quad P_2 \xrightarrow{\alpha} P'_2}{P_1 + P_2 \xrightarrow{\alpha} P'_2}$$

$$\frac{(\text{res}) \quad P \xrightarrow{\alpha} P'}{P \setminus L \xrightarrow{\alpha} P' \setminus L} \quad \alpha, \bar{\alpha} \notin L$$

$$\frac{(\text{rel}) \quad P \xrightarrow{\alpha} P'}{P[f] \xrightarrow{f(\alpha)} P'[f]}$$

$$\frac{(\text{com1}) \quad P \xrightarrow{\alpha} P'}{P|Q \xrightarrow{\alpha} P'|Q}$$

$$\frac{(\text{com2}) \quad Q \xrightarrow{\alpha} Q'}{P|Q \xrightarrow{\alpha} P|Q'}$$

$$\frac{(\text{com3}) \quad P \xrightarrow{a} P' \quad Q \xrightarrow{\bar{a}} Q'}{P|Q \xrightarrow{\tau} P'|Q'}$$

# CCS semantics - building an NFA

$$\begin{array}{c}
 \text{(act)} \\
 \hline
 \alpha.P \xrightarrow{\alpha} P
 \end{array}
 \quad
 \begin{array}{c}
 \text{(sum-1)} \\
 \hline
 \frac{P_1 \xrightarrow{\alpha} P'_1}{P_1 + P_2 \xrightarrow{\alpha} P'_1}
 \end{array}
 \quad
 \begin{array}{c}
 \text{(sum-2)} \\
 \hline
 \frac{P_2 \xrightarrow{\alpha} P'_2}{P_1 + P_2 \xrightarrow{\alpha} P'_2}
 \end{array}$$
  

$$\begin{array}{c}
 \text{(res)} \\
 \hline
 \frac{P \xrightarrow{\alpha} P'}{P \setminus L \xrightarrow{\alpha} P' \setminus L} \quad \alpha, \bar{\alpha} \notin L
 \end{array}
 \quad
 \begin{array}{c}
 \text{(rel)} \\
 \hline
 \frac{P \xrightarrow{\alpha} P'}{P[f] \xrightarrow{f(\alpha)} P'[f]}
 \end{array}$$
  

$$\begin{array}{c}
 \text{(com1)} \\
 \hline
 \frac{P \xrightarrow{\alpha} P'}{P|Q \xrightarrow{\alpha} P'|Q}
 \end{array}
 \quad
 \begin{array}{c}
 \text{(com2)} \\
 \hline
 \frac{Q \xrightarrow{\alpha} Q'}{P|Q \xrightarrow{\alpha} P|Q'}
 \end{array}
 \quad
 \begin{array}{c}
 \text{(com3)} \\
 \hline
 \frac{P \xrightarrow{a} P' \quad Q \xrightarrow{\bar{a}} Q'}{P|Q \xrightarrow{\tau} P'|Q'}
 \end{array}$$

## Ex. 3.12: Draw the NFAs

$CM = \text{coin}.\overline{\text{coffee}}.CM$

$CS = \text{pub}.\overline{\text{coin}}.\text{coffee}.CS$

$SmUni = (CM|CS) \setminus \{\text{coin}, \text{coffee}\}$

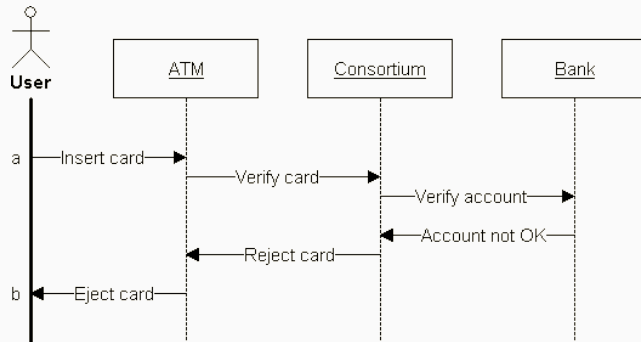
**Ex. 3.13:** Let  $A = b.a.B$ . Show that:

1.  $(A \mid \bar{b}.0) \setminus \{b\} \xrightarrow{\tau} (a.B \mid 0) \setminus \{b\}$
2.  $(A \mid b.a.B) + (b.A)[a/b] \xrightarrow{a} A[a/b]$

# Sequence Diagrams vs. Interactive Processes

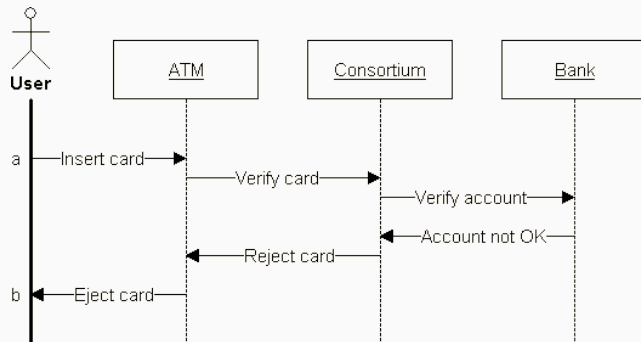
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# Sequence Diagrams as Interactive Processes



- **Objects** as **Processes**  
(e.g., processes  $U$ ,  $A$ ,  $C$ ,  $B$ )
- **Send** actions (e.g., *insertCard*)
- **Receive** actions (e.g.,  $\overline{\text{insertCard}}$ )
- Unique action for each object pair
- Do not write  $(\dots + \mathbf{0})$

# Language of Sequence Diagrams, Informally

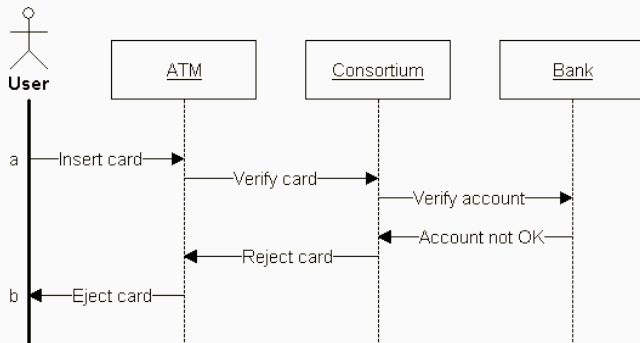


**This example has only 1 word and its prefixes**

$\text{Tr}(sd) = \text{insertCard} \cdot \text{verifyCard} \cdot \text{verifyAccount} \cdot \text{accountNotOK} \cdot$   
 $\text{rejectedCard} \cdot \text{ejectCard}$



# Sequence Diagrams as Interactive Processes



**Ex. 3.14: Write an interactive processes that acts as above**

$Sys = (U|A|C|E)$   
 $U = \overline{insertCard}.ejectCard.0$   
 $A = \dots$   
 $C = \dots$   
 $E = \dots$