SEN9110 Simulation Masterclass Lecture 4. The DEVS formalism

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Brightspace: SEN9110

Agenda of this lecture

- Questions about paper last class
- System specification levels (Klir, Zeigler)
- Trajectories (Vangheluwe, Zeigler)
- The DEVS model (Zeigler)

Topic 1: Levels of System Specification

From: Chapter 1 from Zeigler, B. P., H. Praehofer and T. G. Kim (2000). Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems, (2nd Ed.) Academic Press, NY.

Retrieved from: http://acims.asu.edu/wp-content/uploads/2012/02/Introduction-to-Systems-Modeling-Concepts.pdf

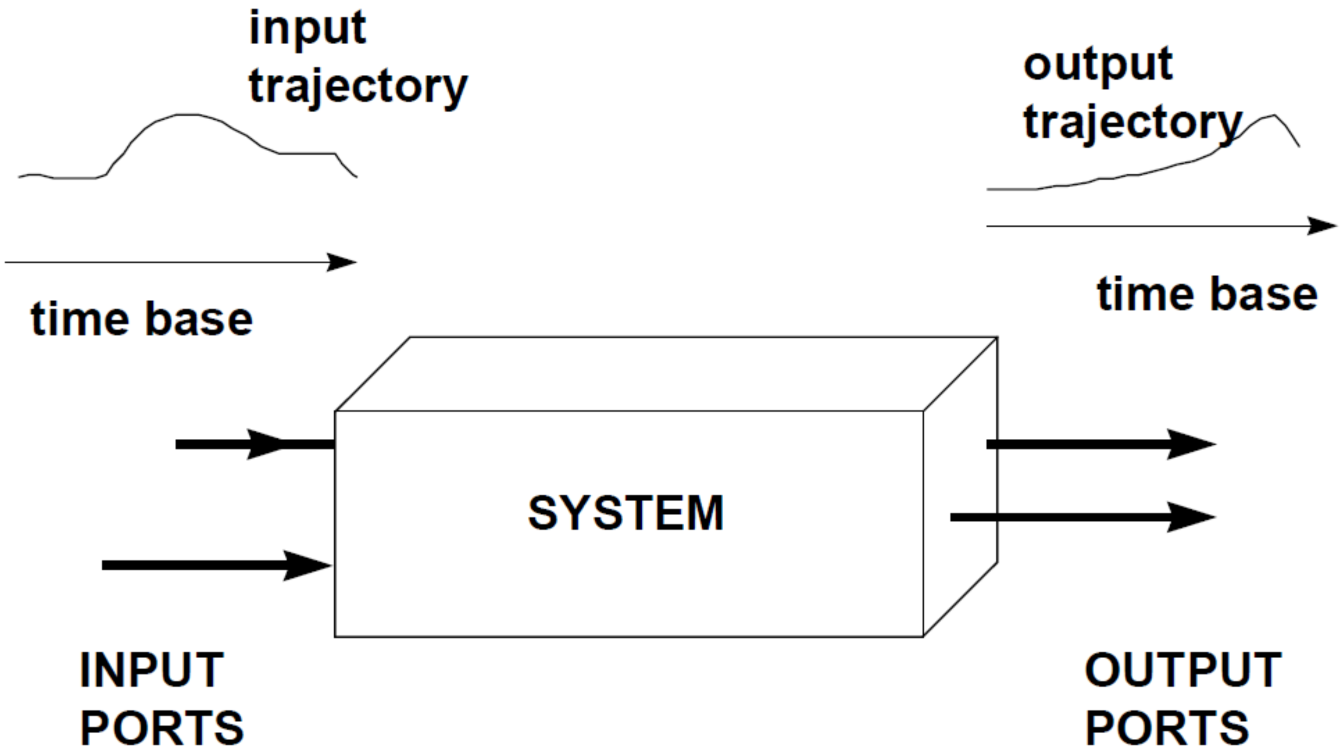
Levels of System Knowledge (Klir)

Level	Name	What we know at this level
0	Source	what variables to measure and how to observe them
1	Data	data collected from a source system
2	Generative	means to generate data in a data system
3	Structure	components (at lower levels) coupled together to form a generative system

Relation between Zeigler's System Specification Hierarchy and Klir’s levels

Level	Specification name	Klir's level	What we know at this level
0	Observation Frame	Source System	how to stimulate the system with inputs; what variables to measure and how to observe them over a time base
1	I/O Behavior	Data System	time-indexed data collected from a source system; consists of input/output pairs
2	I/O Function		knowledge of initial state; given an initial state, every input stimulus produces a unique output
3	State Transition	Generative System	how states are affected by inputs; given a state and an input what is the state after the input stimulus is over; what output event is generated by a state
4	Coupled Component	Structure System	components and how they are coupled together. The components can be specified at lower levels or can even be structure systems themselves – leading to hierarchical structure

Input / Output System



Source: Zeigler et al. (2000).
Theory of Modeling and Simulation

Time Base

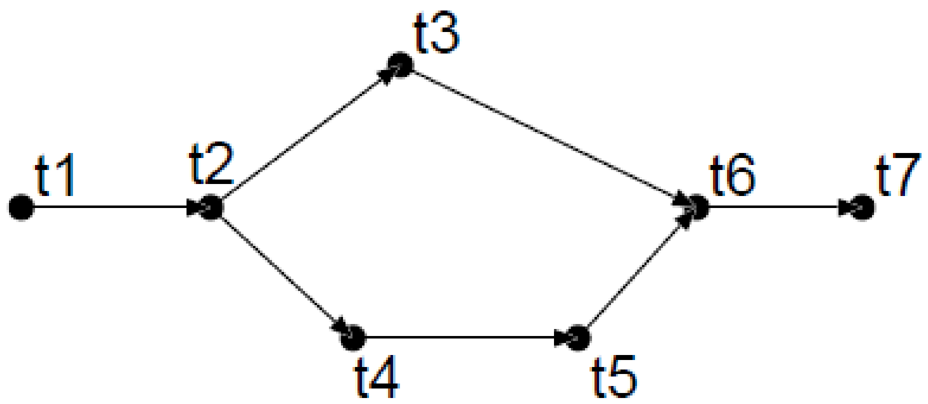
Time Base = (T, $<$)

Where:

T is a set, and $<$ is an ordering relation.

$<$ is transitive, irreflexive and antisymetric

$<$ can be a total or partial ordering relation



Source: Hans Vangheluwe. System Specification
http://msdl.cs.mcgill.ca/people/hv/teaching/MoSIS/

Time Base

Continuous time base: $\Re$ = (R, <), where R is the set of reals and < is a total ordering relation.

Discrete time base: $\Im$ = (c*I, <), where c $\in$ R, and I is the set of integers (c*I is isomorphic with I)

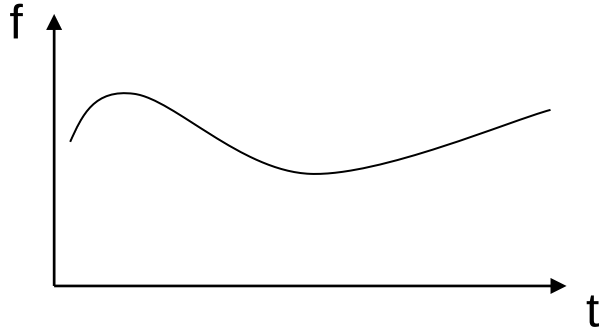
0.1 * I = {.1,.2,.3,.4,.5,.6,.7,.8,.9,1,1.1,…}
< is a total ordering relation

Trajectory

A trajectory is a function or mapping **f**, defined from a time base **T** to a set **A** (input, output, state)

$$\mathbf{f : T \rightarrow A}$$

The value of **f** at each instant is given by **f(t)**



Segment

A segment ω is a restriction of a trajectory to a certain time interval.

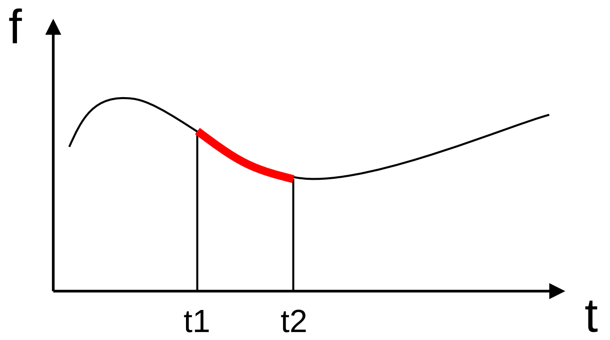
$$\omega : \langle t1,t2\rangle \rightarrow A$$

Also written $\omega_{\langle t1,t2\rangle}$

Domain(ω) $= \langle t1,t2\rangle$

Range(ω) $= A$

Segments denote a motion through the range set between times t1 and t2.



Segment

Two segments $\boldsymbol{\omega_1}$ and $\boldsymbol{\omega_2}$ defined as follows :

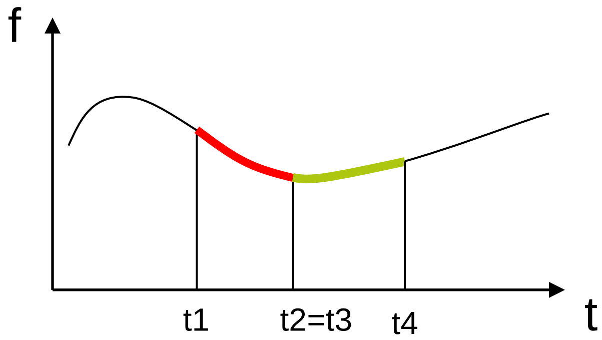
$$\boldsymbol{\omega_1 : \langle t1,t2 \rangle \rightarrow A}$$

$$\boldsymbol{\omega_2 : \langle t3,t4 \rangle \rightarrow A}$$

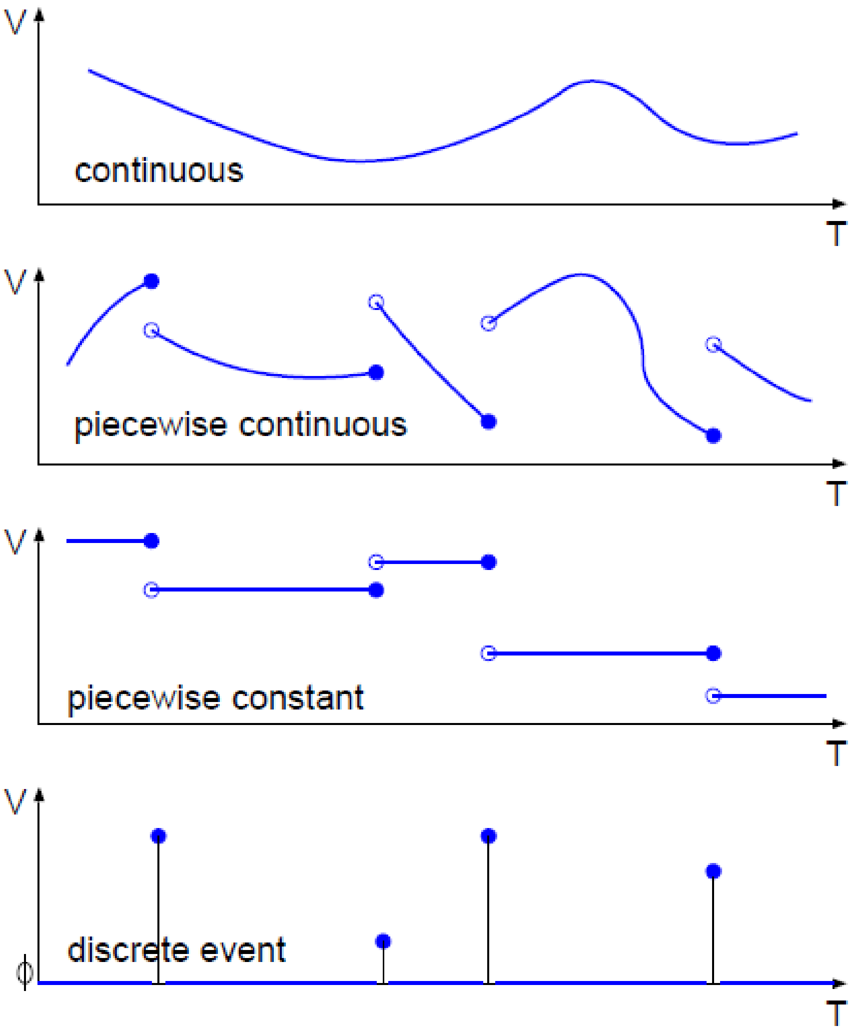
are contiguous if t2 = t3.

Concatenation operation denoted •, such that

$\boldsymbol{\omega 1 \bullet \omega 2 : \langle t1,t4 \rangle \rightarrow A}$



Segment



Source: Hans Vangheluwe. System Specification
http://msdl.cs.mcgill.ca/people/hv/teaching/MoSIS/

Zeigler's System Specification Hierarchy

Level	Specification name	What we know at this level
0	Observation Frame	how to stimulate the system with inputs; what variables to measure and how to observe them over a time base
1	I/O Behavior	time-indexed data collected from a source system; consists of input/output pairs
2	I/O Function	knowledge of initial state; given an initial state, every input stimulus produces a unique output
3	State Transition	how states are affected by inputs; given a state and an input what is the state after the input stimulus is over; what output event is generated by a state
4	Coupled Component	components and how they are coupled together. The components can be specified at lower levels or can even be structure systems themselves – leading to hierarchical structure

Source: Zeigler et al. (2000). Theory of Modeling and Simulation

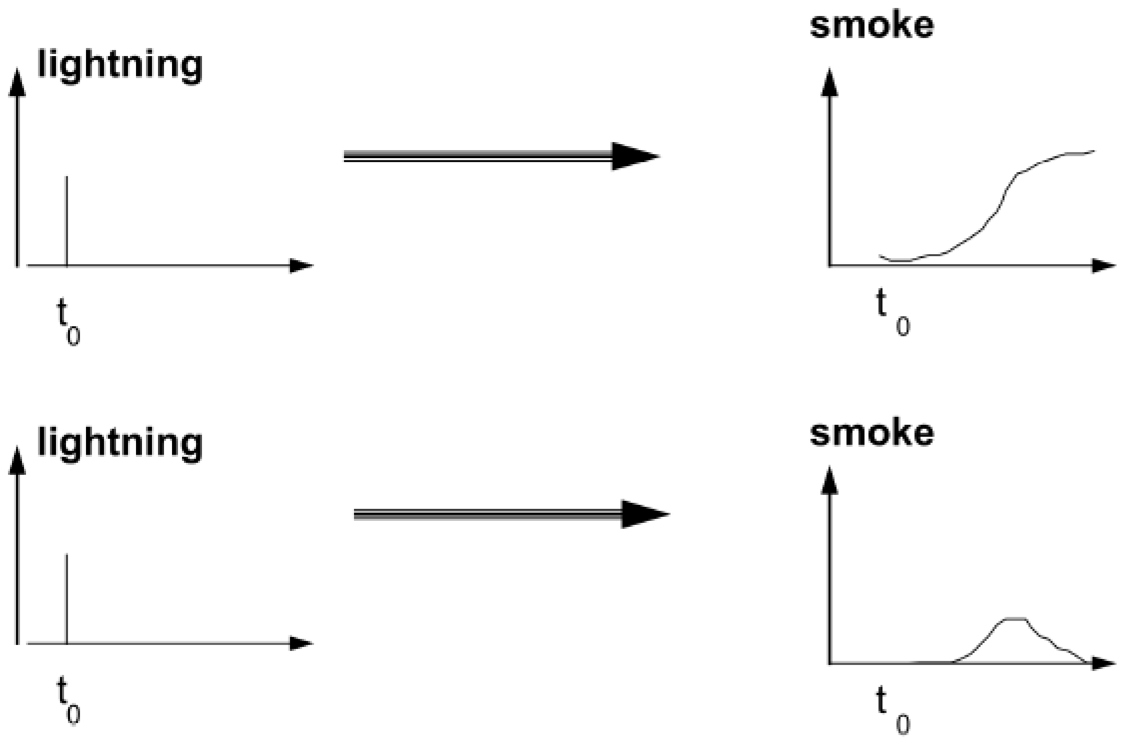
Observation Frame (level 0)

Level 0:

How to stimulate the system with inputs; what variables to measure and how to observe them over a time base

Source: Zeigler et al. (2000).
Theory of Modeling and Simulation

I/O Behavior (level 1)

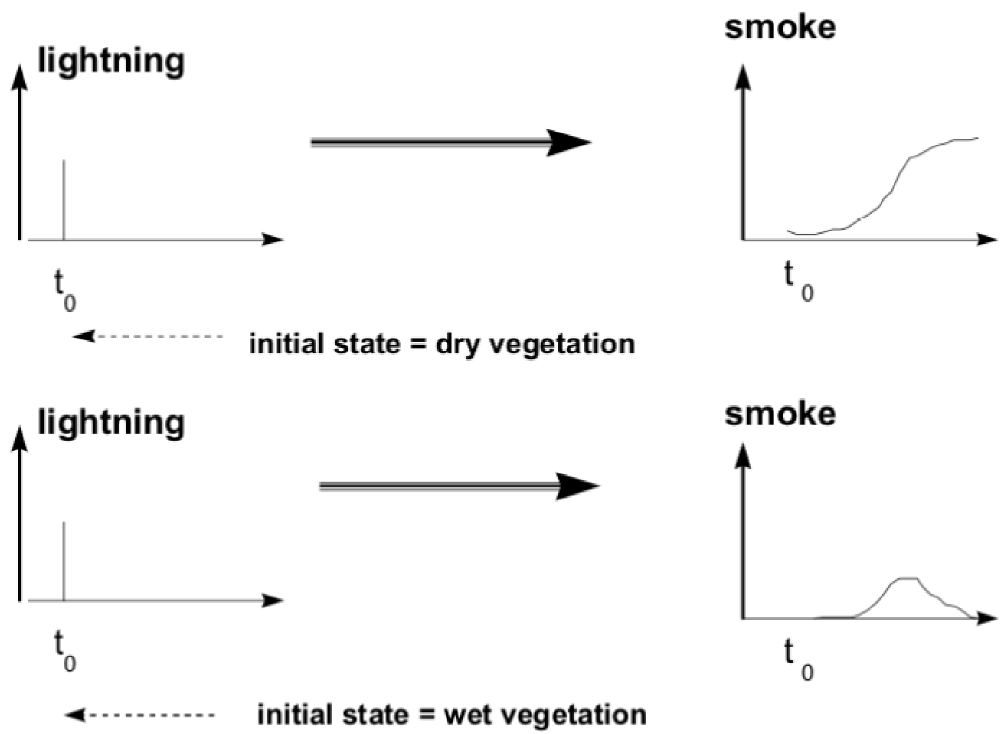


Level 1:

Time-indexed data collected from a source system; consists of input/output pairs

Source: Zeigler et al. (2000).
Theory of Modeling and Simulation

I/O Function (level 2)

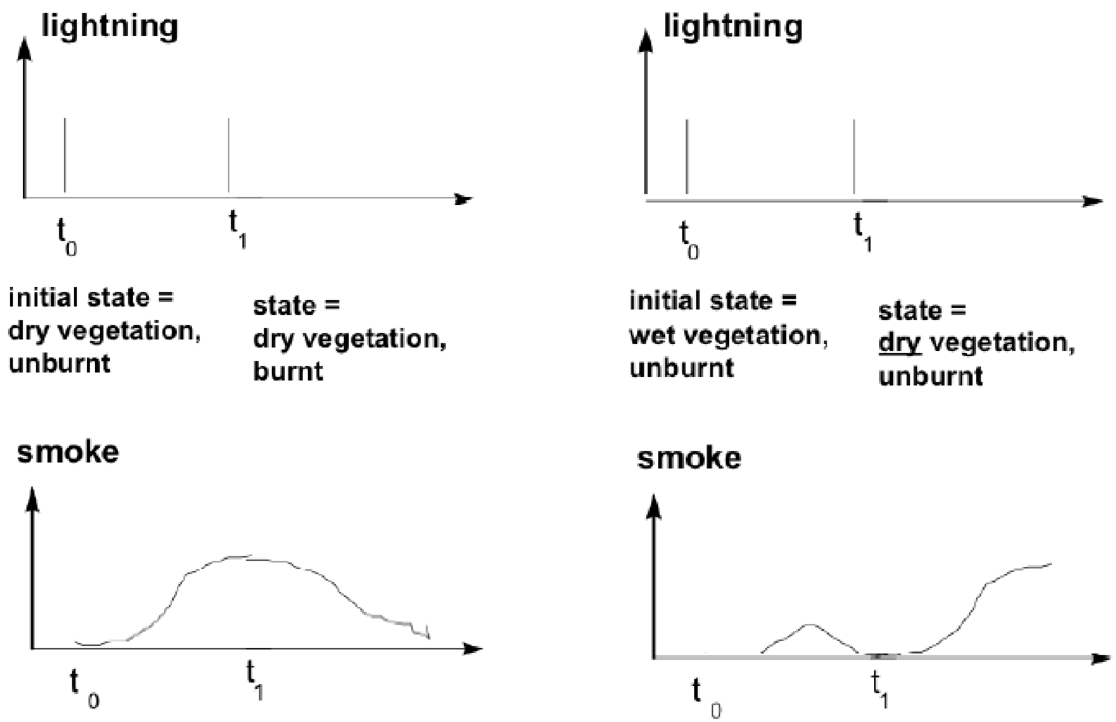


Level 2:

Knowledge of initial state; given an initial state, every input stimulus produces a unique output

Source: Zeigler et al. (2000).
Theory of Modeling and Simulation

State Transition (level 3)

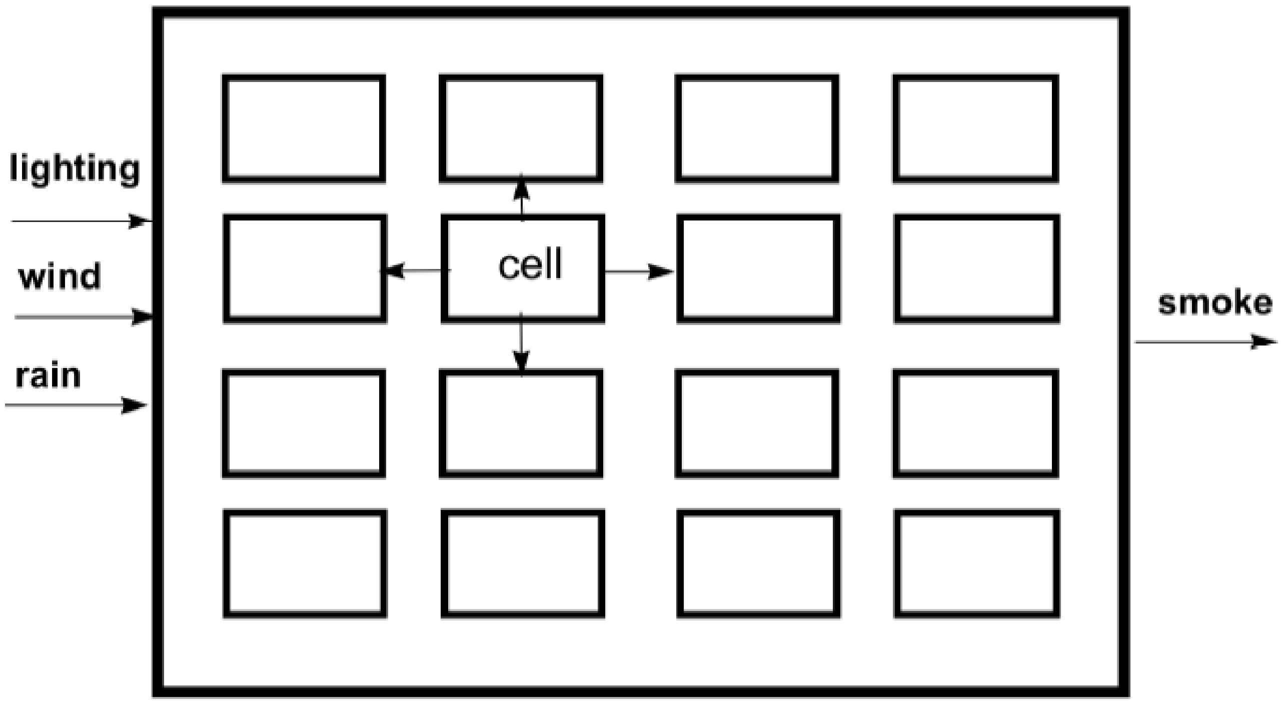


Level 3:

How states are affected by inputs; given a state and an input what is the state after the input stimulus is over; what output event is generated by a state

Source: Zeigler et al. (2000). Theory of Modeling and Simulation

Coupled Component (level 4)



Level 4:

Components and how they are coupled together. The components can be specified at lower levels or can even be structure systems themselves – leading to hierarchical structure

Source: Zeigler et al. (2000).
Theory of Modeling and Simulation

Topic 2: DEVS

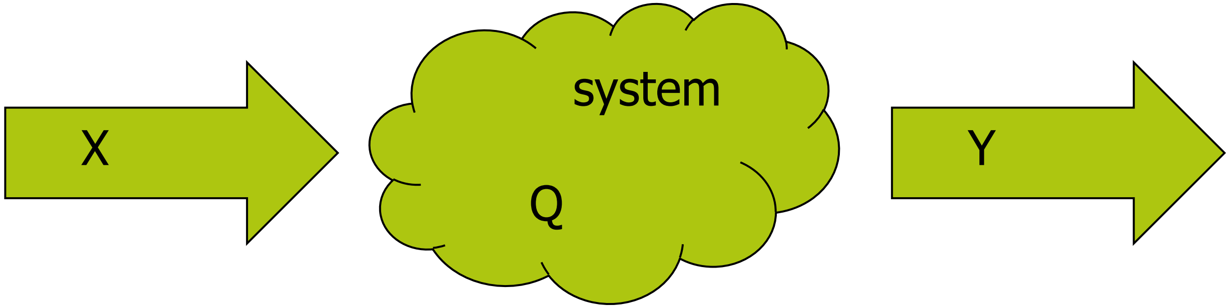
Reading: Yentl Van Tendeloo, Hans Vangheluwe. Introduction to Parallel DEVS Modelling and Simulation. SpringSim-Tutorial, 2017 April 23-26, Virginia Beach, VA, USA. SCS, 2017.

Retrieved from: http://msdl.cs.mcgill.ca/people/yentl/papers/2017-DEVSTutorial.pdf

General Systems Theory: System / Model

Wymore, 1967

$SYS \equiv \langle T, X, \Omega, Q, \delta, Y, \lambda \rangle$	
T	Time base
X	Input set
$\omega \in \Omega : T \rightarrow X$	Input segment
Q	State set
$\delta : \Omega \times Q \rightarrow Q$	Transition function
Y	Output set
$\lambda : Q \rightarrow Y$	Output function



Wymore, A. W. (1967). *A Mathematical Theory of Systems Engineering. the Elements*, Wiley.

Example Wymore

$T = \mathbb{R}^{+} \cup \{0\}$
$X = \{x_1\}, x_1 \in \mathbb{N}$
$\omega_1: x_1(t) = \mathit{floor}(t)$
$Q = \{q_1, q_2, q_3\}, q_1, q_2, q_3 \in \mathbb{N}$
$\delta_1: q_1(w, Q) = w \ \mathit{mod}\ 60$
$\delta_2: q_2(w, Q) = \mathit{floor}(w / 3600)$
$\delta_3: q_3(w, Q) = \mathit{floor}(w / 60) - 60 * q_2$
$Y = \{y_1, y_2, y_3\}, y_1, y_2, y_3 \in \mathbb{N}$
$\lambda_1: y_1 = q_2$
$\lambda_2: y_2 = q_3$
$\lambda_3: y_3 = q_1$

Question 1: What does the system do?
Question 2: What is the time base?

SYS ≡ <T, X, Ω, Q, δ, Y, λ>

T	Time base
X	Input set
$\omega \in \Omega : T \rightarrow X$	Input segment
Q	State set
$\delta : \Omega \times Q \rightarrow Q$	Transition function
Y	Output set
$\lambda : Q \rightarrow Y$	Output function

the *floor* function returns the integer part of a number without the fraction after the decimal point

the *mod* function *mod(a,b)* returns the integer rest an integer division of a by b.

DEVS

The *Discrete Event System Specification (DEVS)* assumes that the time base is continuous and that the trajectories in the system database are piecewise constant, i.e., the state variables remain constant for variable periods of time. The jump-like state changes are called *events*. The models specify how events are scheduled and what state transitions they cause. Associated simulators handle the processing of events as dictated by the models.

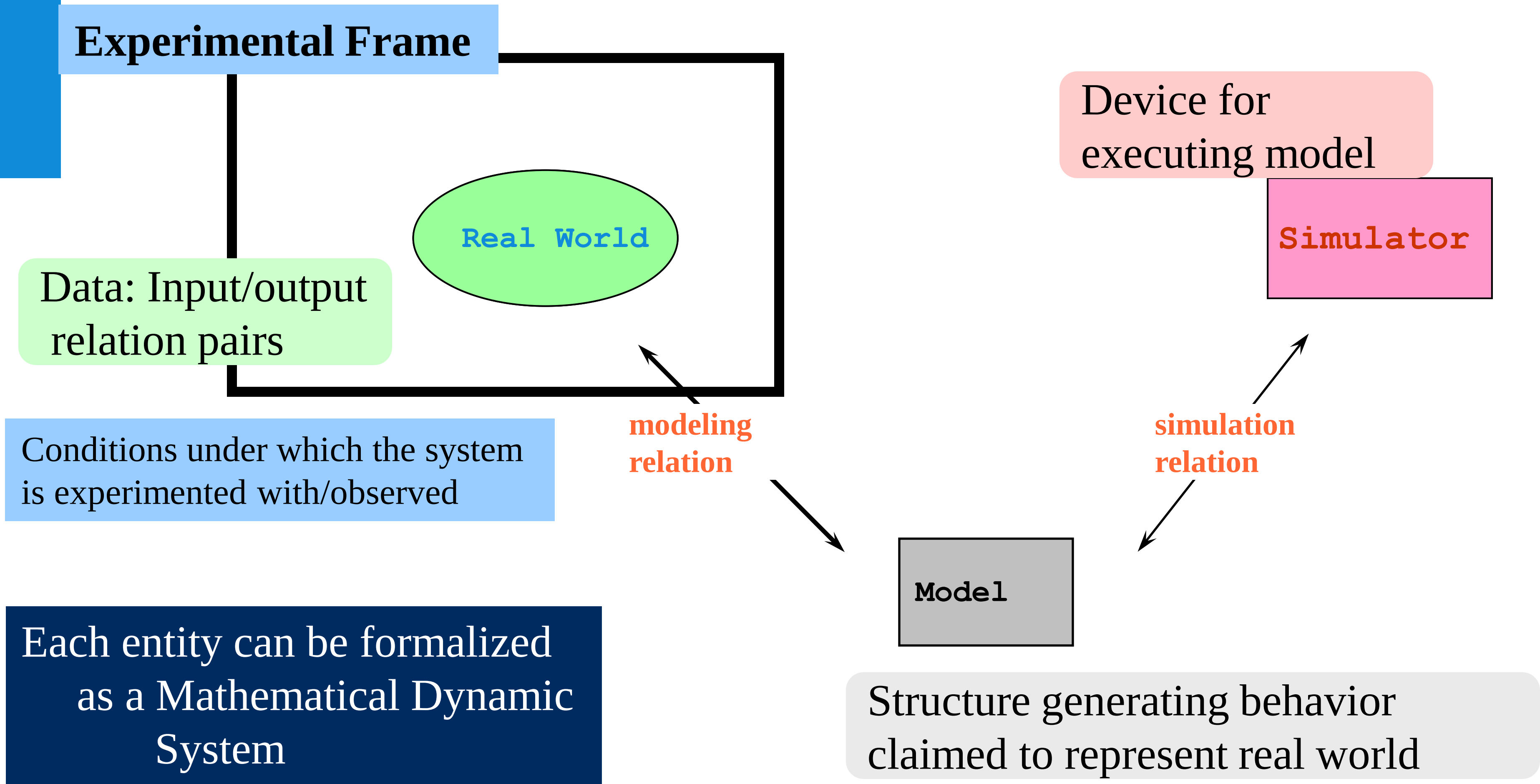
Ref: Hild, 2000

The DEVS Framework for M&S

- Derived from Generic Dynamic Systems Formalism
  - Includes Continuous/Discrete Time Systems
- Well Defined Coupling of Components
- Supports
  - Hierarchical Construction
  - Stand Alone Testing
  - Repository Reuse

Source: Wainer, Dagstuhl workshop 04041

Separation of concerns in DEVS



Each entity can be formalized as a Mathematical Dynamic System
(mathematical manipulations to prove system properties)

Ref: Prof. B. Zeigler (ACIMS)

Terminology (1)

- **Real System**: source of data (behavior)
  - Organization

- **Model**: Set of instructions for generating data comparable to that in real system
  - Mathematical Model

- **Simulator**: Executes the model's instructions to actually generate behavior
  - DEVS processor on computer

Terminology (2)

- **Experimental Frame**: Specifies conditions under which the system is experimented with and observed
- **Modeling Relation**: How the model represents the real system being modeled
- **Simulation relation**: How the simulator is able to carry out the instruction of the model

DEVS Atomic Model Specification

DEVS = $< \mathbf{X}, \mathbf{S}, \mathbf{Y}, \delta_{int}, \delta_{ext}, \delta_{con}, ta, \lambda >$

$\boldsymbol{X}$: a set of input events

$\boldsymbol{Y}$: a set of output events

$\boldsymbol{S}$: a set of states

$ta: \mathbf{S} \rightarrow \mathbf{R}^{+}_{\mathbf{0}, \infty}$ time advance function

$\delta_{int}: \mathbf{S} \rightarrow \mathbf{S}$ internal transition function

$\delta_{ext}: \mathbf{Q} \times \mathbf{X}^{b} \rightarrow \mathbf{S}$ external transition function

$\delta_{con}: \mathbf{Q} \times \mathbf{X}^{b} \rightarrow \mathbf{S}$ confluent transition function

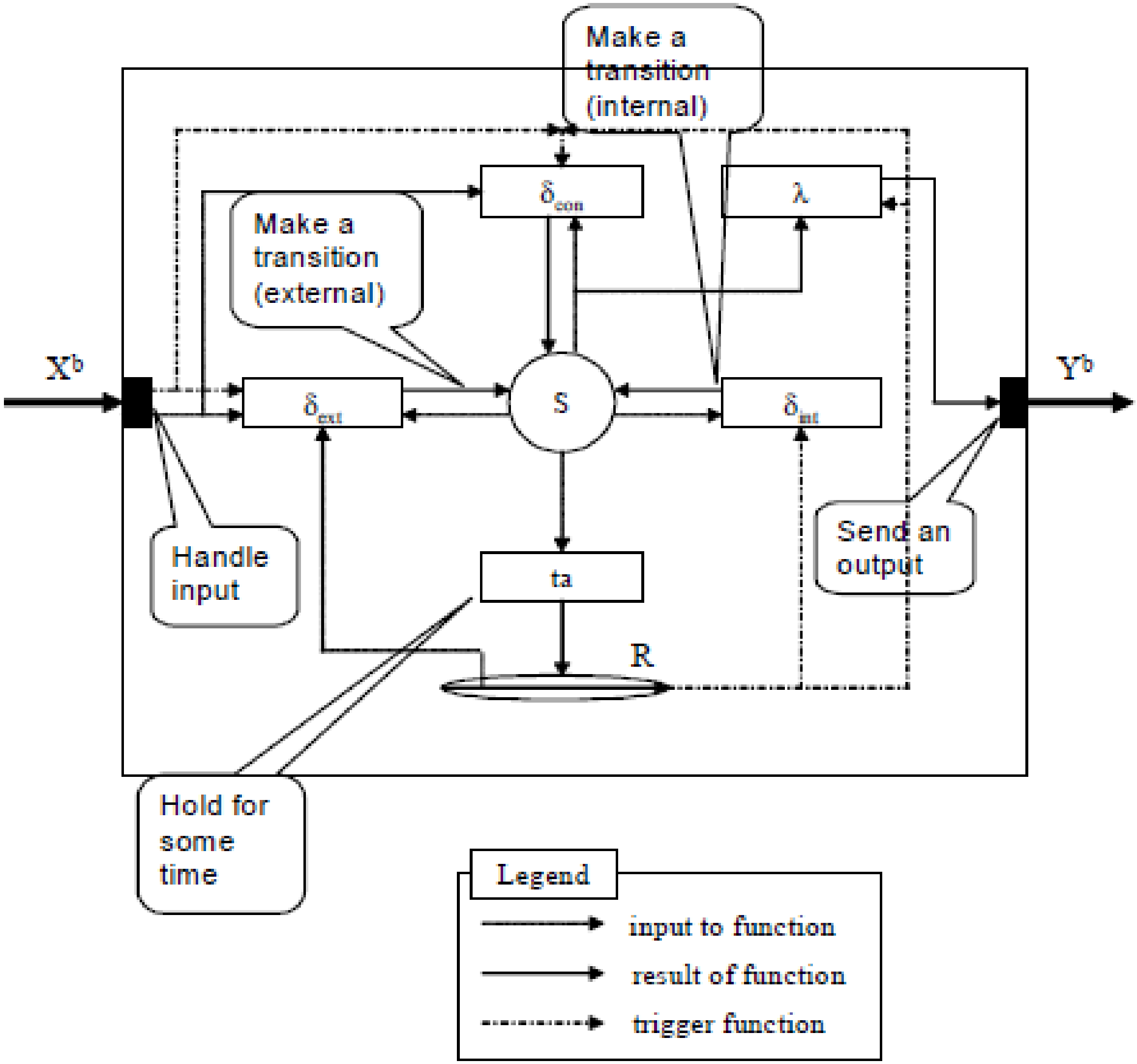
where $\mathbf{X}^{b}$ is a set of bags over elements in $\mathbf{X}$

$$\mathbf{Q} = \{(\mathbf{s},\mathbf{e}) \mid \mathbf{s} \in \mathbf{S}, \mathbf{0} \leq \mathbf{e} \leq ta(s)\}$$

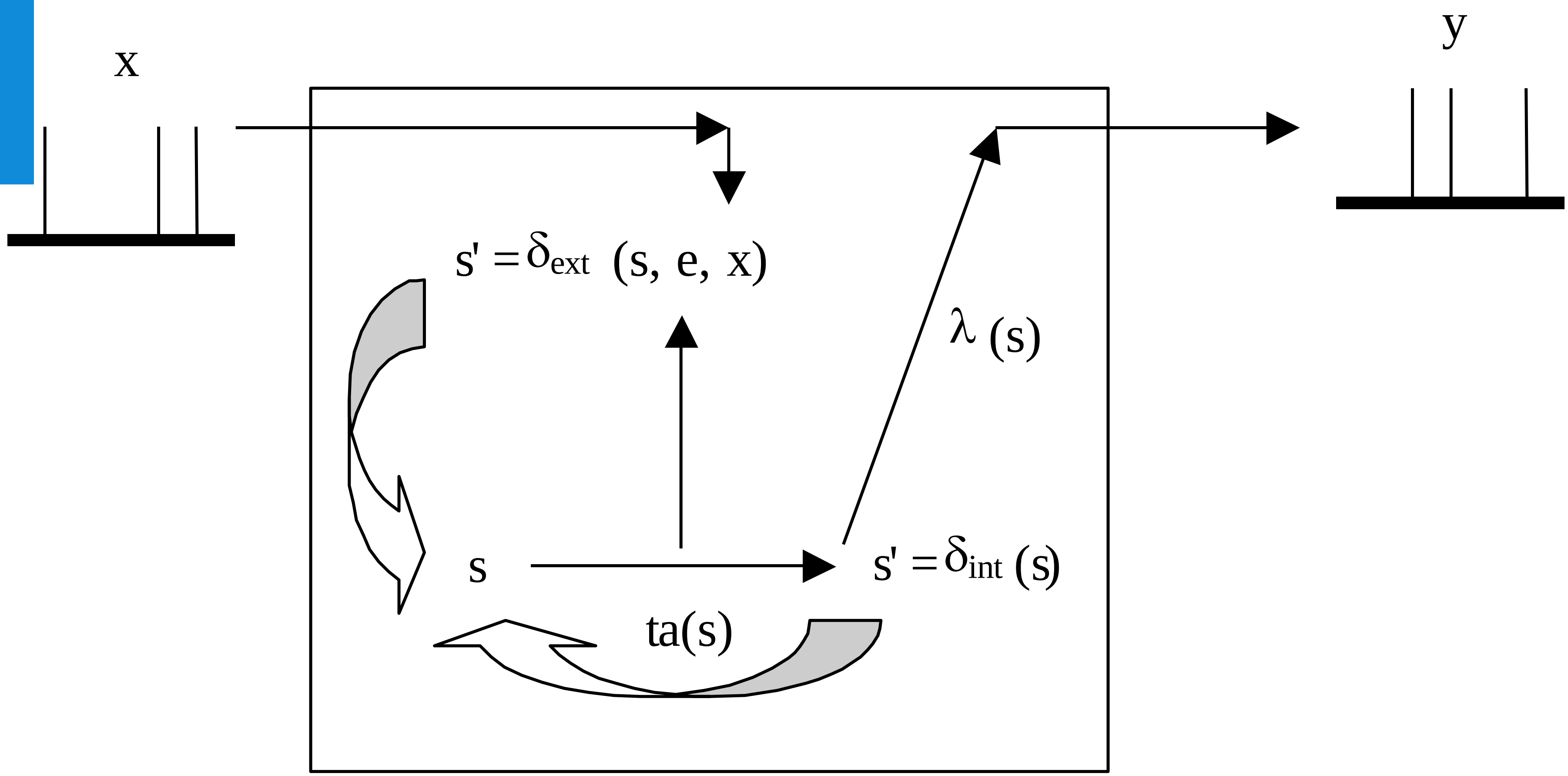
$\lambda: \mathbf{S} \rightarrow \mathbf{Y}$ output function

Ref: Prof. B. Zeigler (ACIMS)

DEVS operation

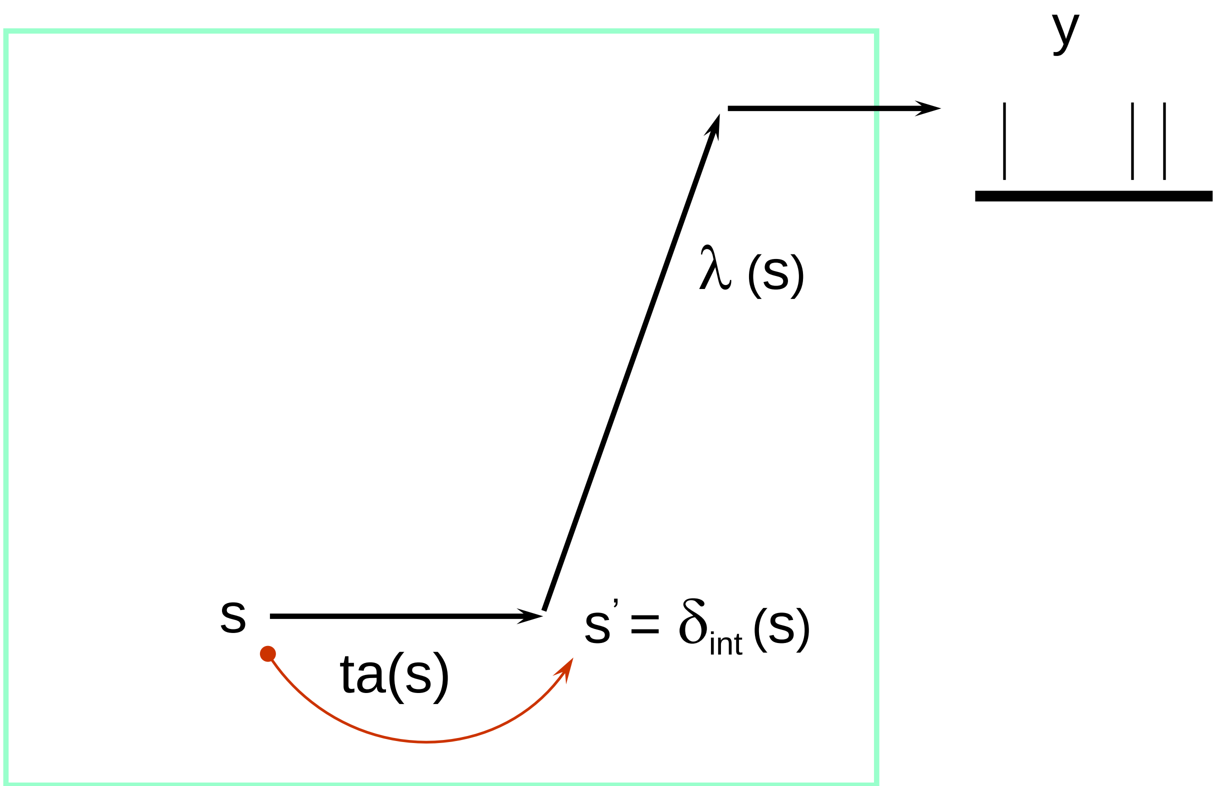


DEVS Atomic models behavior



Source: Wainer, Dagstuhl workshop 04041

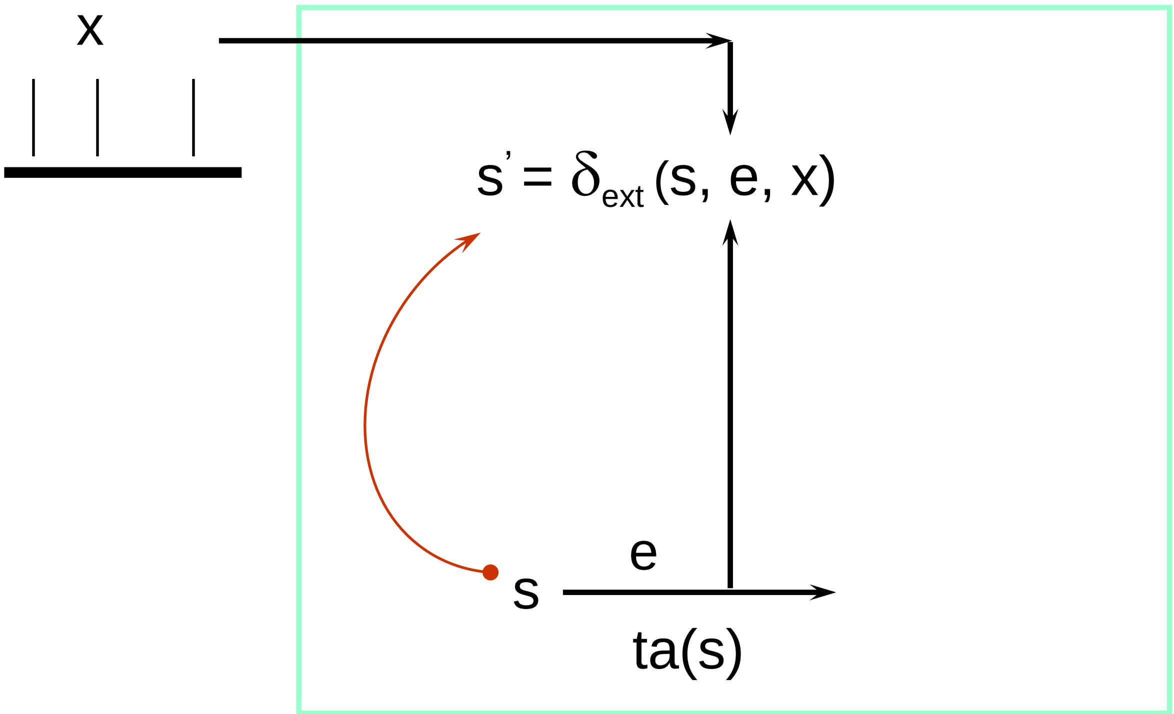
Internal Transition Function/Output Function



$$DEVS = < X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, ta, \lambda >$$

Ref: Prof. B. Zeigler (ACIMS)

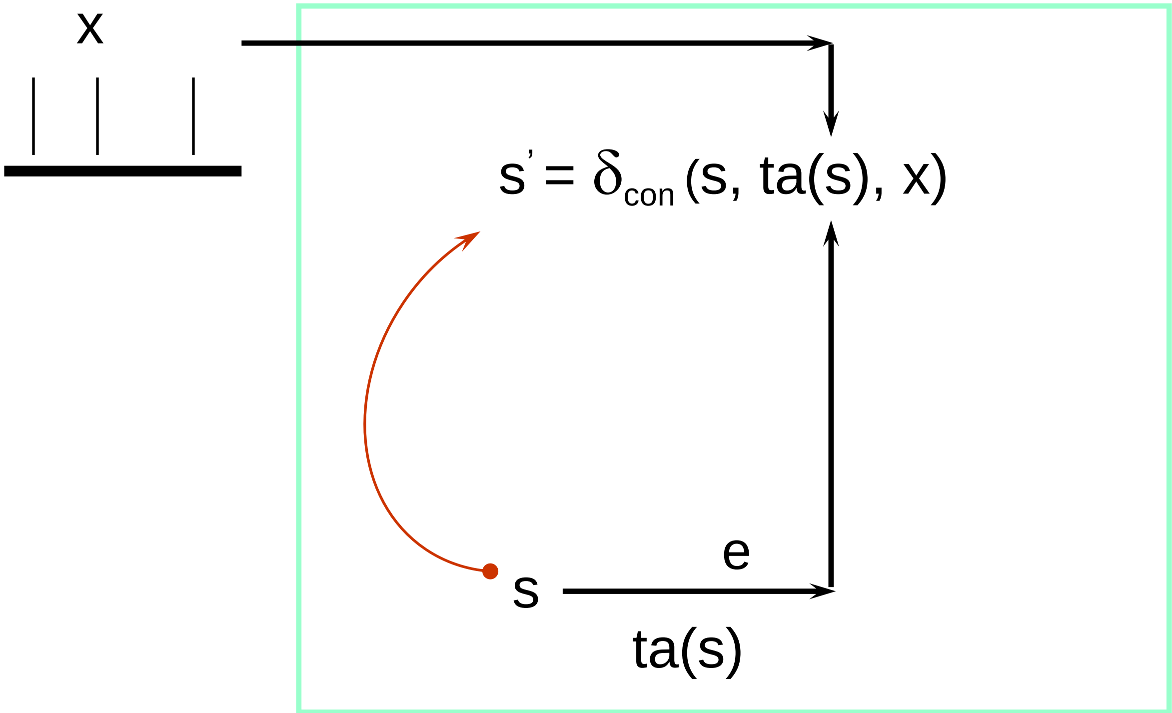
External Transition Function



$$\text{DEVS} = \langle X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, ta, \lambda \rangle$$

Ref: Prof. B. Zeigler (ACIMS)

Confluent Transition Function



$$DEVS = \langle X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, ta, \lambda \rangle$$

Ref: Prof. B. Zeigler (ACIMS)

DEVS Formalism

- System is in State s
- If no external event occurs, system will stay in s for time period given by ta(s)
- After ta(s) time, i.e. e=ta(s), system outputs λ(s)
- If external event occur (δ_{ext}) the new state is determined by x, current state s, and e
- e = how long the system was in that state

Ref: Prof. B. Zeigler (ACIMS)

Transition functions

- Internal transitions generates output
- System stays in state "s" for time ta before making internal transition and generating output
- External transitions: in response to external input; it does not generate output

Ref: Prof. B. Zeigler (ACIMS)

Homework

- Read Zeigler chapter and paper
- Prepare questions if unclear

- Work on term papers
- Work on Simulation Package Assignment 1 (see deadline!)