v1.0
BETA

Sistemi Concorrenti e di Rete LS

II Facoltà di Ingegneria - Cesena
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[module 2.4]

VISUAL FORMALISMS FOR CONCURRENT SYSTEMS

VISUAL FORMALISMS

- Formalisms for rigorously describing models of concurrent systems by means of some kind of visual diagrams
  - structural and behavioural aspects
- Useful for both requirement specification / analysis and design
  - formal analysis when formally specified
- Formalisms considered in this module
  - Petri Nets
  - Statecharts
  - Activity Diagrams

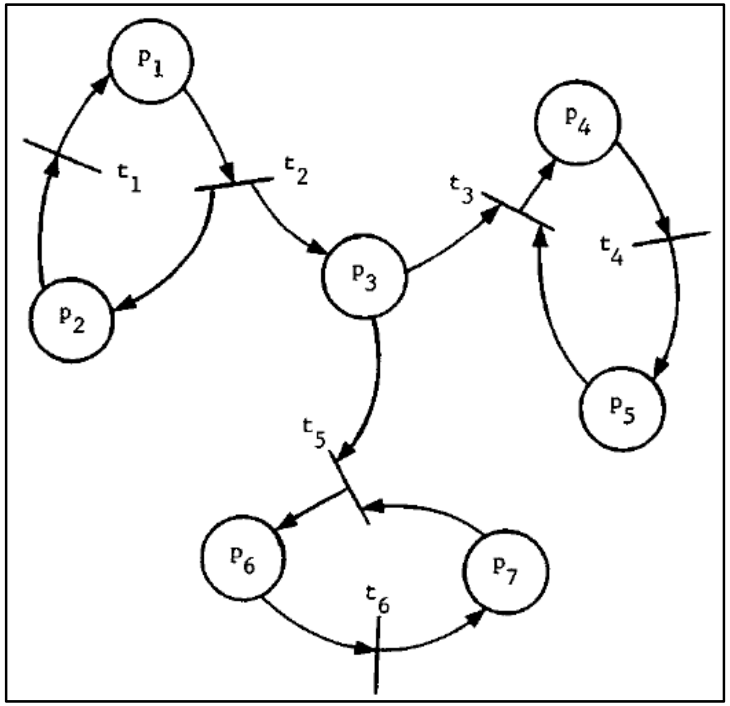
PETRI NETS

PETRI NETS

- Abstract, formal model of information flow
  - describing and analyzing the *flow of information* and *control* in systems
  - particularly systems that may exhibits asynchronous and concurrent activities
- Introduced by Carl Adam Petri ~ 1965
  - further developed, extended and adopted in many computer science contexts
- Major use
  - modelling of systems of events in which it is possible for some events to occur concurrently but there are constraints on the concurrence, precedence, or frequency of these occurrences

PETRI NET GRAPH

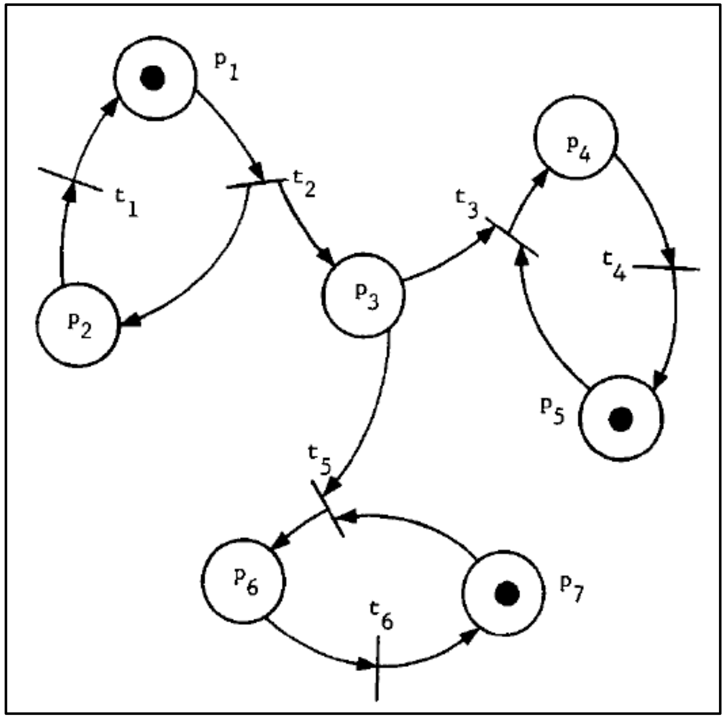
- Bi-partite graphs representing a Petri Net
  - two types of *nodes*
    - **places** (the circles) and **transitions** (the bars)
  - connected by directed arcs
    - from node i to node j: i is an input to j and i is an output of i



- Models the static properties of the system

TOKENS

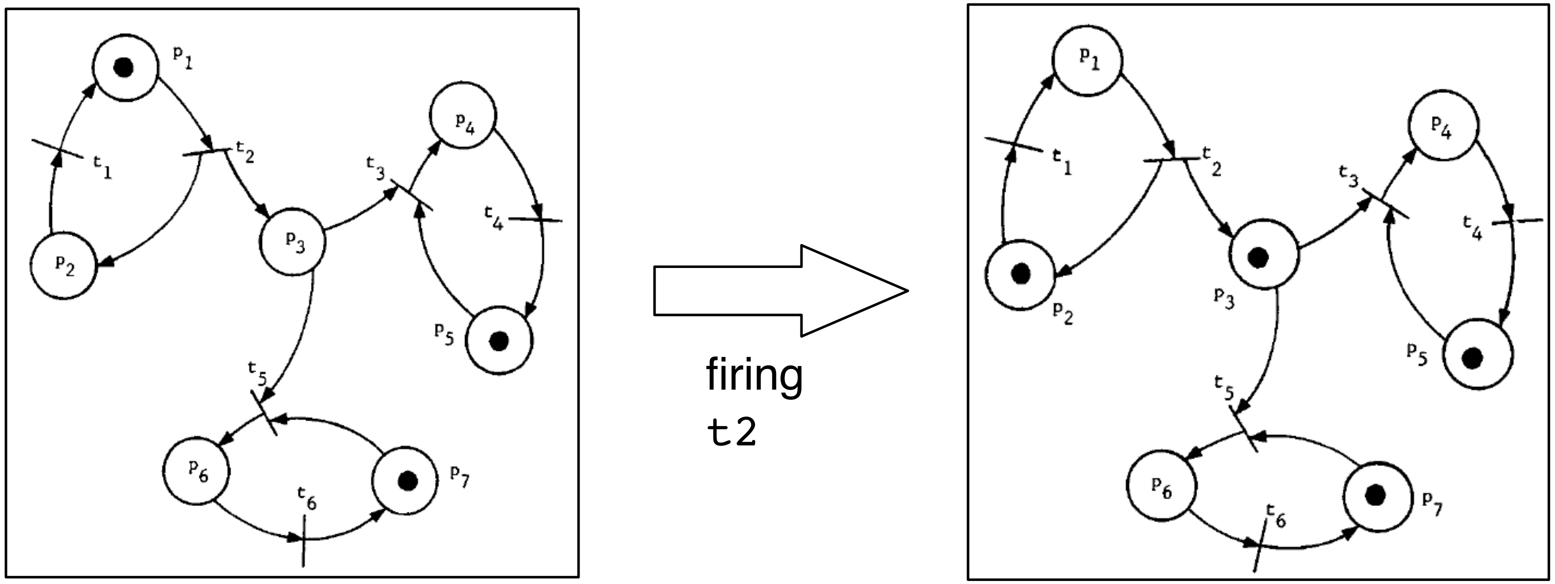
- In addition to the static properties represented by the graph, a Petri Net has *dynamic properties* that result from its *execution*
  - the execution of a Petri net is controlled by the position and movement of markers called **tokens** in the net.



  - tokens are indicated by black dots, residing in places
- A Petri Net with tokens is called **marked Petri Net**

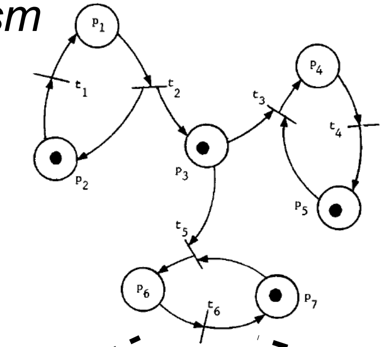
EXECUTION RULES

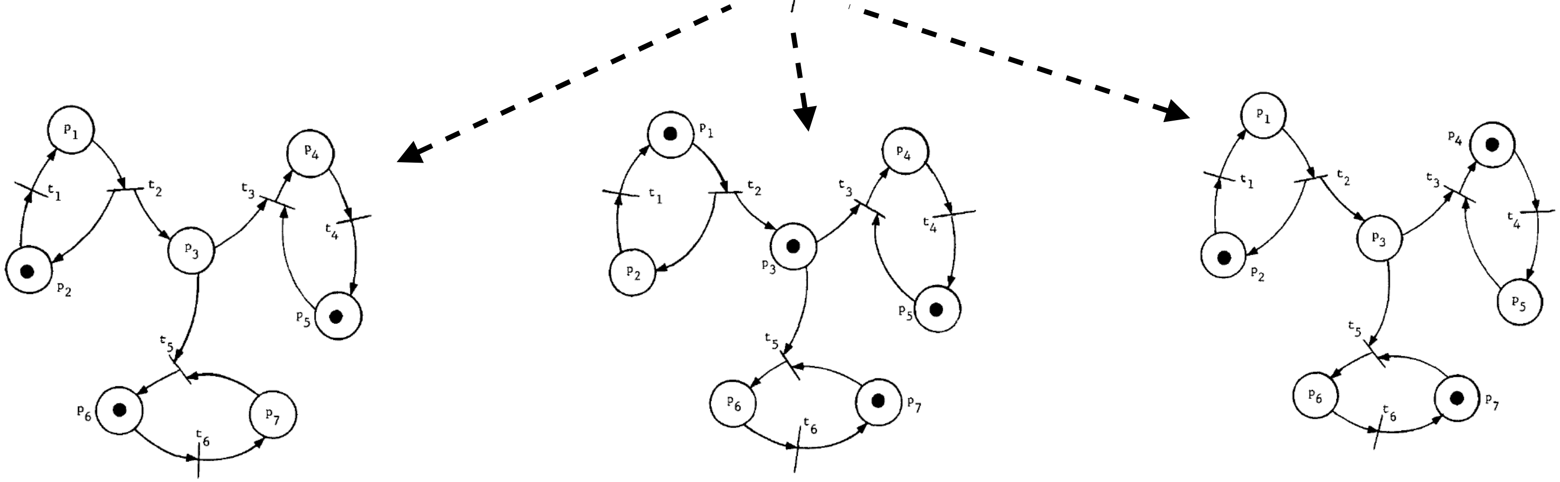
- Tokens are moved by the *firing* of transitions of the net
  - a transition must be *enabled* in order to fire
    - a transition is enabled when all of its input places have a token in them
  - the transition fires by removing the enabling tokens from their input places and generating new tokens which are deposited in the output place of the transition



MARKINGS

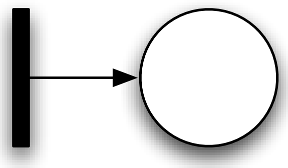
- The distribution of tokens in a marked Petri Net defines the state of the net and is called **marking**
  - the marking may change as a result of firing transitions
- Different transitions may fire, with different result markings
  - inherent *non-determinism*



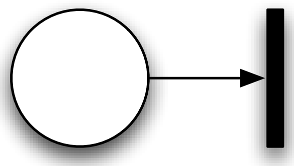


TRANSITIONS ON THE BOUNDARY

- *source* transition
  - without any input place
  - just produce tokens



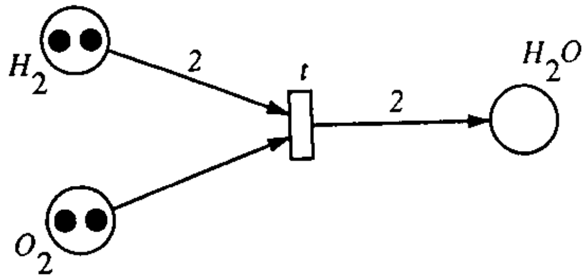
- *sink* transition
  - without any output place
  - just consume tokens

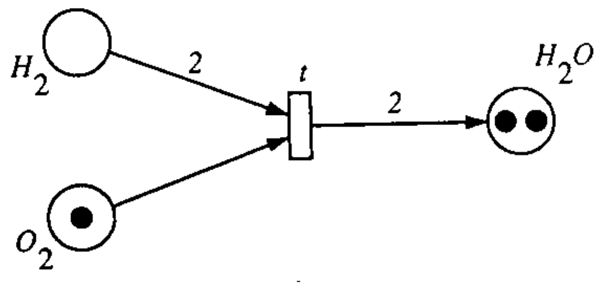


WEIGHTED ARCS

- A variant consider also weights for arcs:
  - a transition is enabled if each input place p of t is marked with at least w(p,t) tokens, where w(p,t) is the weight of the arc from p to t
  - a firing of an enabled transition t removes w(p,t) tokens from each input place p of t, and adds w1 tokens to each output place p of t, where w(t,p) is the weight of the arc from t to p

- Reaction example
  - $2H_2 + O_2 \rightarrow 2H_2O$

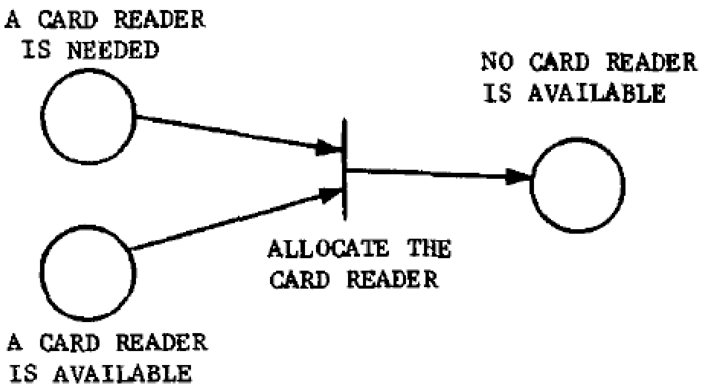


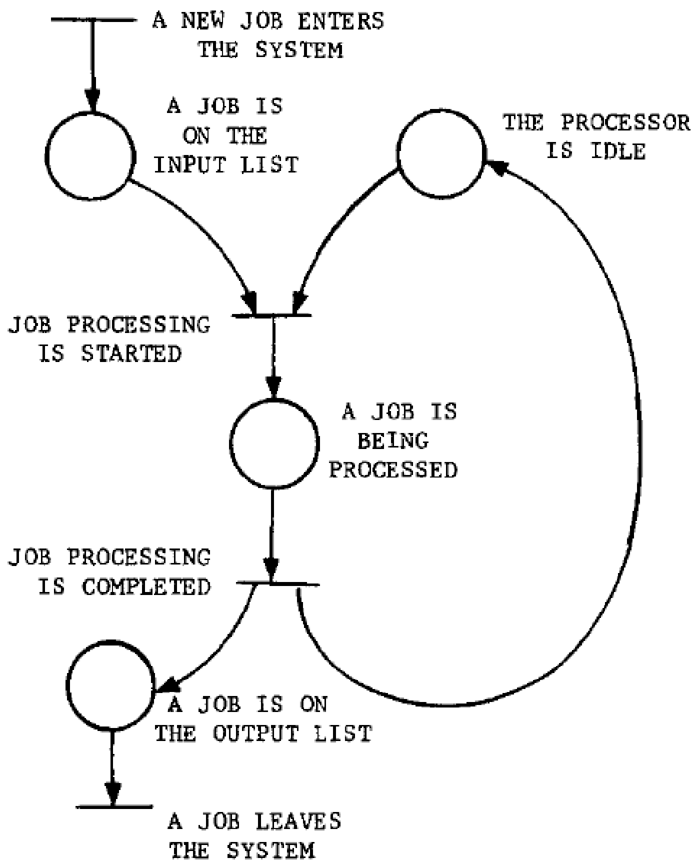


MODELING WITH PETRI NETS

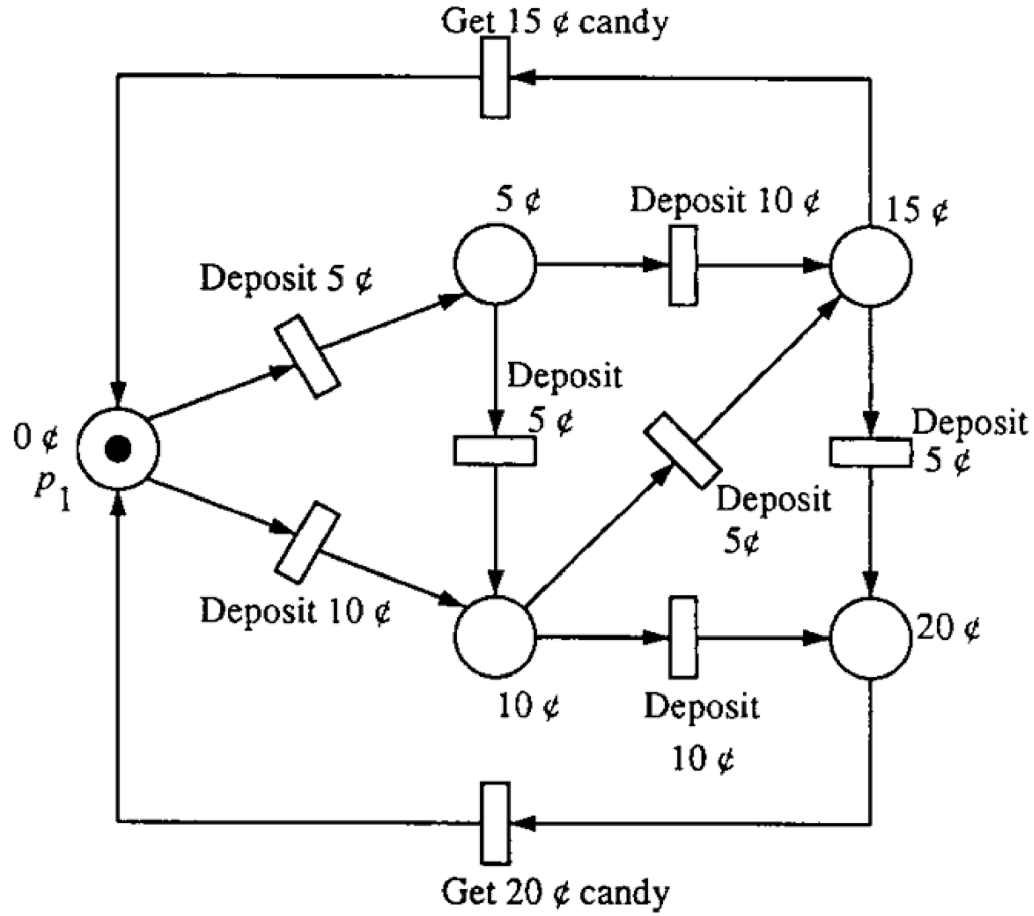
- Petri nets can be used to model quite naturally concurrent systems in terms of:
  - **events** and **conditions**
  - the relationships among them
- Interpretation
  - in a system at any given time certain conditions will hold
  - the fact that these conditions hold may cause the occurrence of certain events
  - the occurrence of events may change the state of the system
    - causing some of the previous conditions to cease holding and causing other conditions to begin to hold
  - firing of a transition = occurrence of an event
    - considered instantaneous or better: atomic change of the system

EXAMPLE: RESOURCE ALLOCATION





EXAMPLE: A VENDING MACHINE



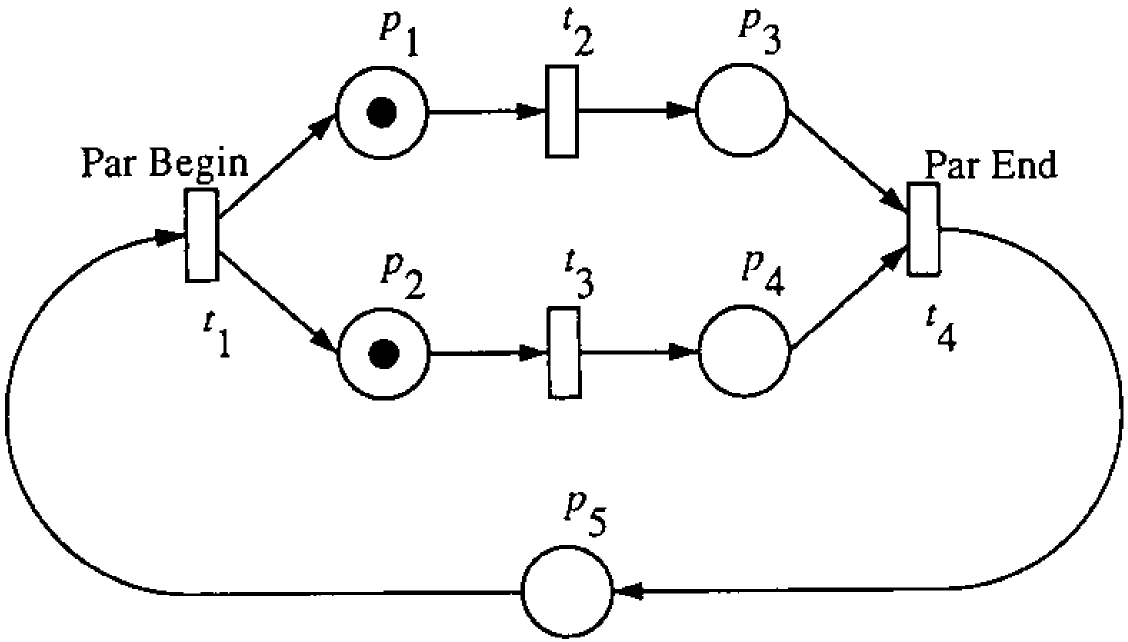
INTERPRETATIONS

- Typical intepretations of places and transitions

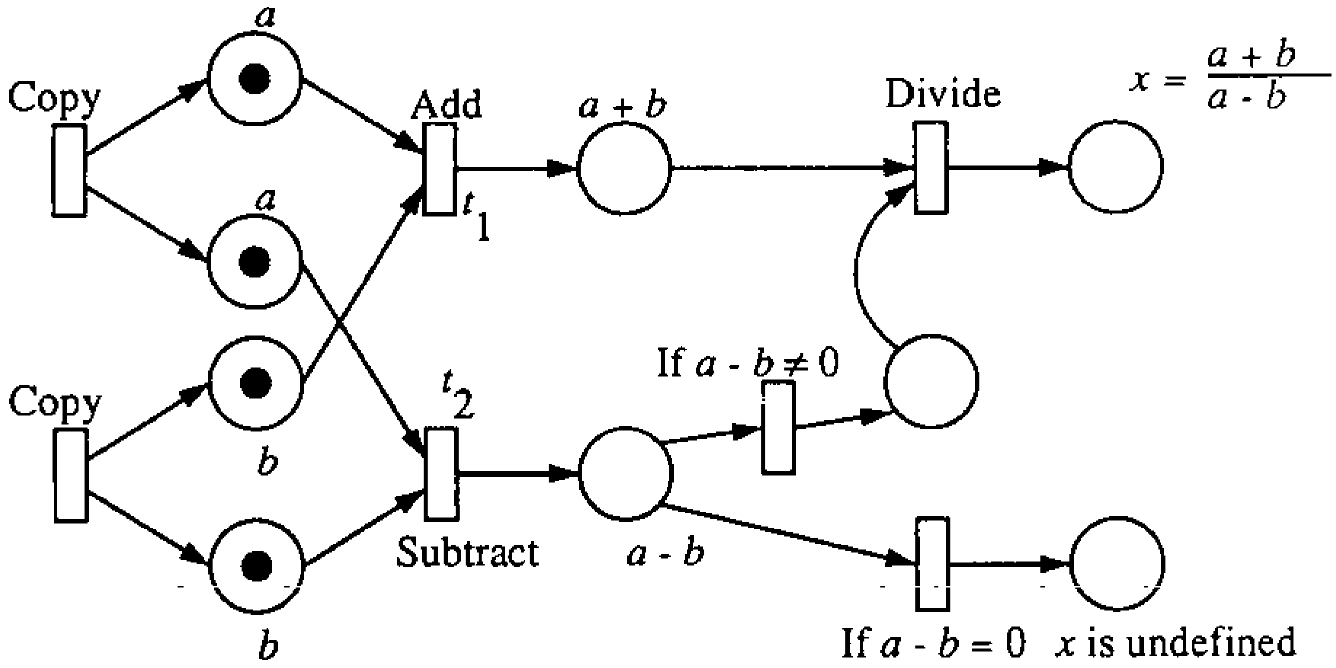
Input places	Transition	Output places
Pre-conditions	Event	Post-conditions
Input data	Computational step	output data
Input signals	Signal processor	Output signals
Resource needed	Task or Job	Resource Released
Conditions	Clause in Logic	Conclusion(s)
Buffers	Processor	Buffers

MODELLING CONCURRENCY AND PARALLELISM

- PN are ideal for modelling systems of distributed control with multiple processes occurring concurrently

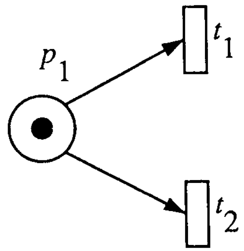


DATA-FLOW COMPUTATION

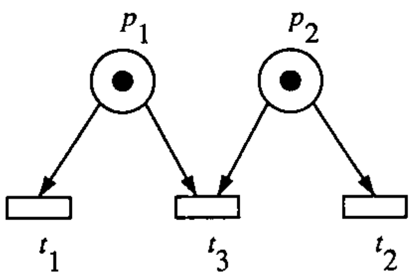


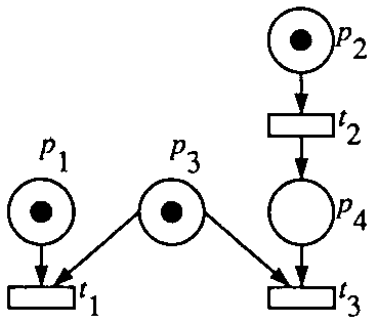
MODELLING CONFLICT AND CONCURRENT EVENTS

- Representing conflicting or choice events:



- *Conflict* vs. *concurrent* events
  - two events e1 and e2 are *in conflict* if either e1 or e2 can occur but not both
  - two events e1 and e2 are *concurrent* if both events can occur in any order without conflicts
- A situation where conflict and concurrency are mixed is called a *confusion*





ASYNCHRONY AND LOCALITY

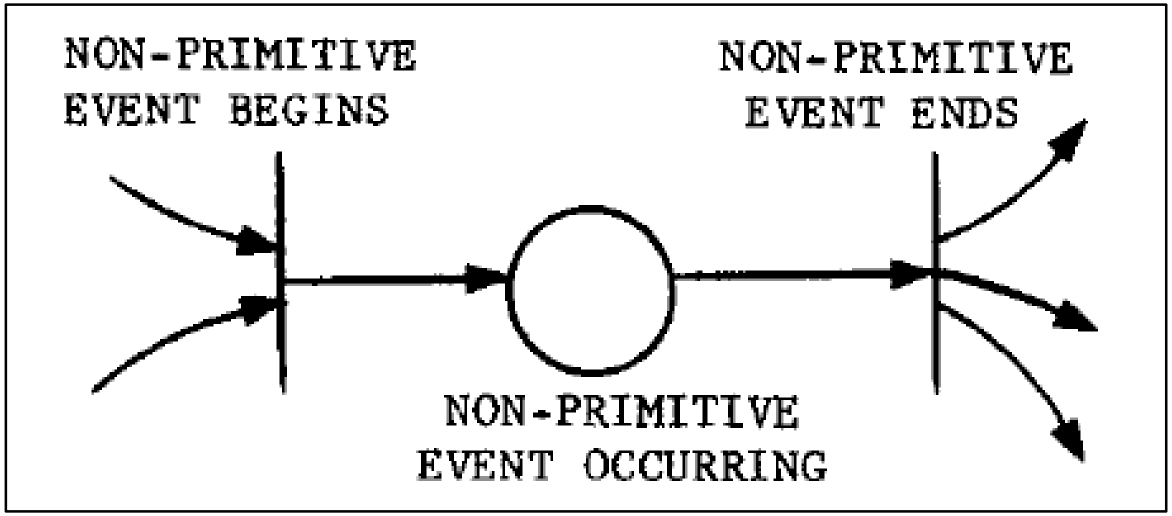
- In a PN there is no inherent measure of time or the flow of time
  - the only important property of time, from a logical point of view, is in defining a **partial ordering** of the occurrence of events
  - events which need not be constrained in terms of their relative order of occurrence are not constrained
- Locality
  - in a complex systems composed by independent asynchronously operating subparts each part can be modelled by a Petri Net
  - the enabling and firing of transitions are then affected by, and in turn affect only, *local changes* in the marking of the Petri Net

NON-DETERMINISM

- Naturally modelling non deterministic behaviours
  - a PN is viewed as a sequence of discrete events whose order of occurrence is one of the possibly many allowed by the basic structure
  - if at any time more than one transition is enabled, then any of the several enabled transitions may fire
  - the choice as to which transition fires is made in a nondeterministic manner
    - randomly or by forces that are not modelled

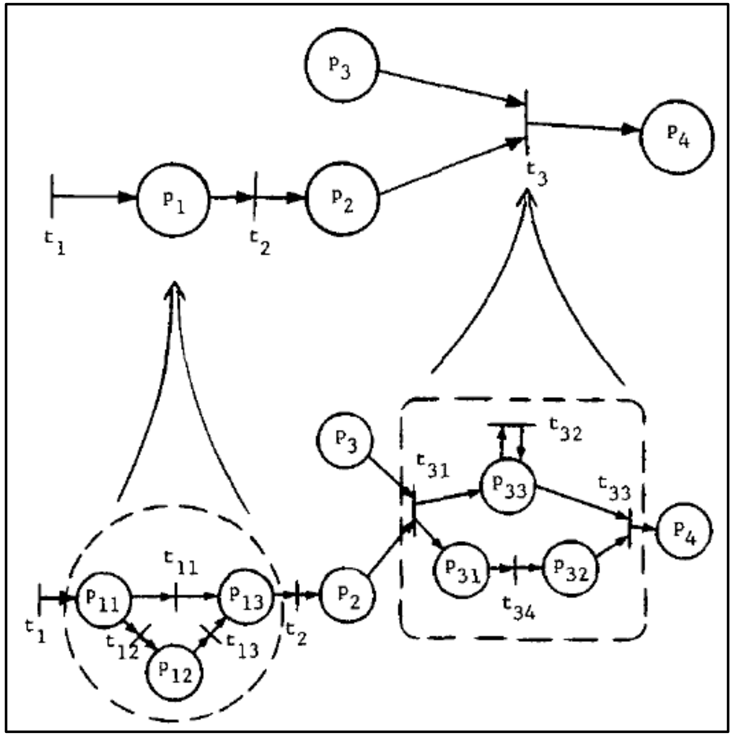
ATOMIC VS. NON-ATOMIC EVENTS

- The occurrence of (primitive) events is instantaneous
  - non primitive events (with a duration) must be modelled by multiple events
  - e.g.: activity with a beginning and an ending event



HIERARCHIES

- Natural support to model hierarchies
  - an entire net may be replaced by a single place or transition for modelling at a more abstract level (**abstraction**)
  - places and transitions may be replaced by subnets to provide more detailed modeling (**refinement**)

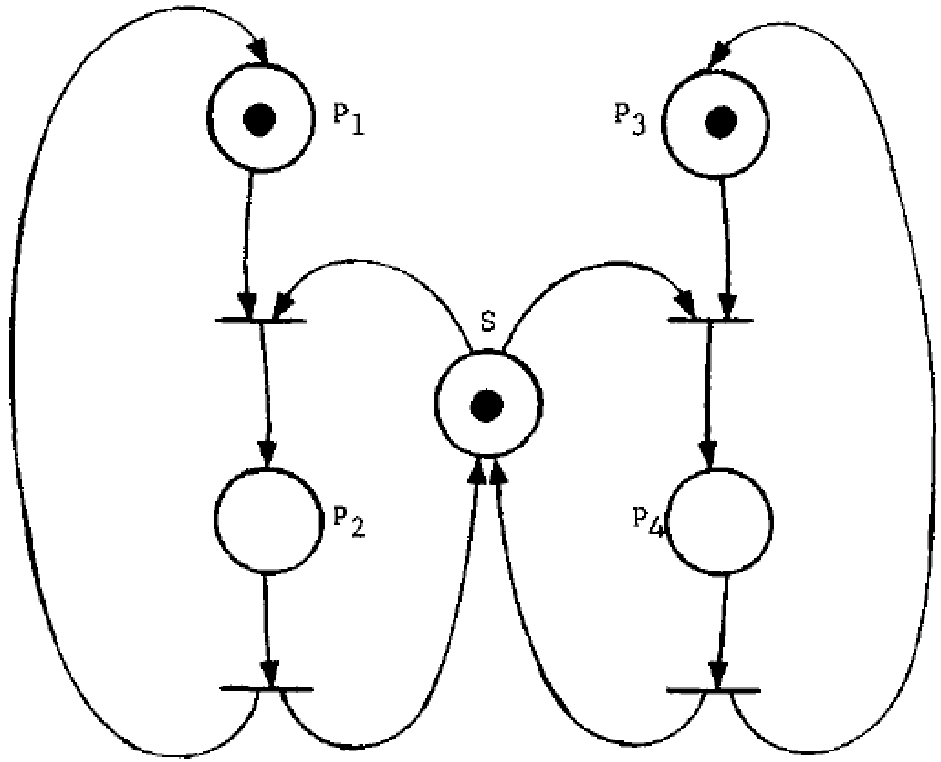


APPLICATION TO CONCURRENT DESIGN AND PROGRAMMING

- PN can be natually used to model software systems, concurrent software systems in particular
- Representing problems
  - critical sections and mutual exclusion problems
  - synchronization
- Representing mechanisms behaviour
  - semaphores
  - synchronizers
- Representing entire problems
  - Producers / Consumers
  - Readers-Writers
  - Dinining Philosophers

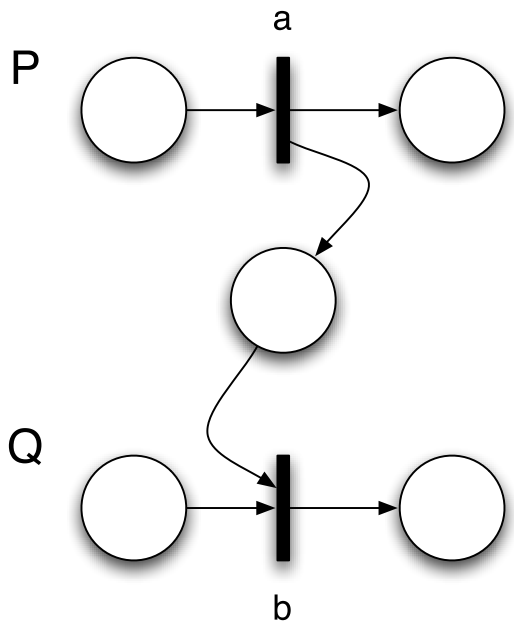
CRITICAL SECTION AND MUTUAL EXCLUSION PROBLEMS

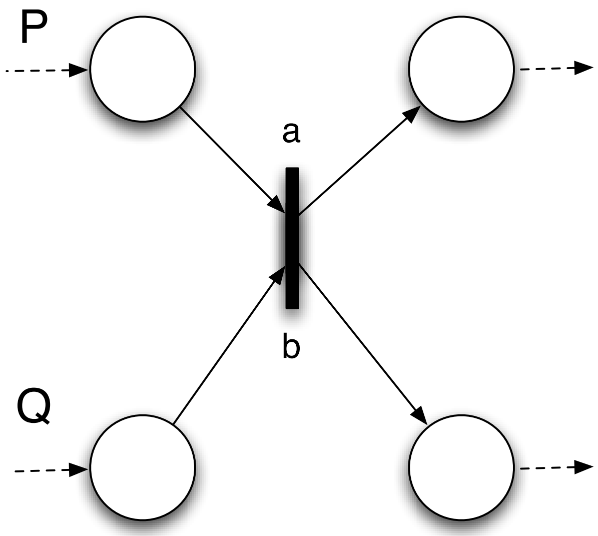
- p2 and p4 represent critical sections
  - s is the token needed for entering in CS



SYNCHRONIZATION

- Imposing an order between process actions
  - process actions represented by transitions
  - relating actions (transitions) trhough conditions (places)

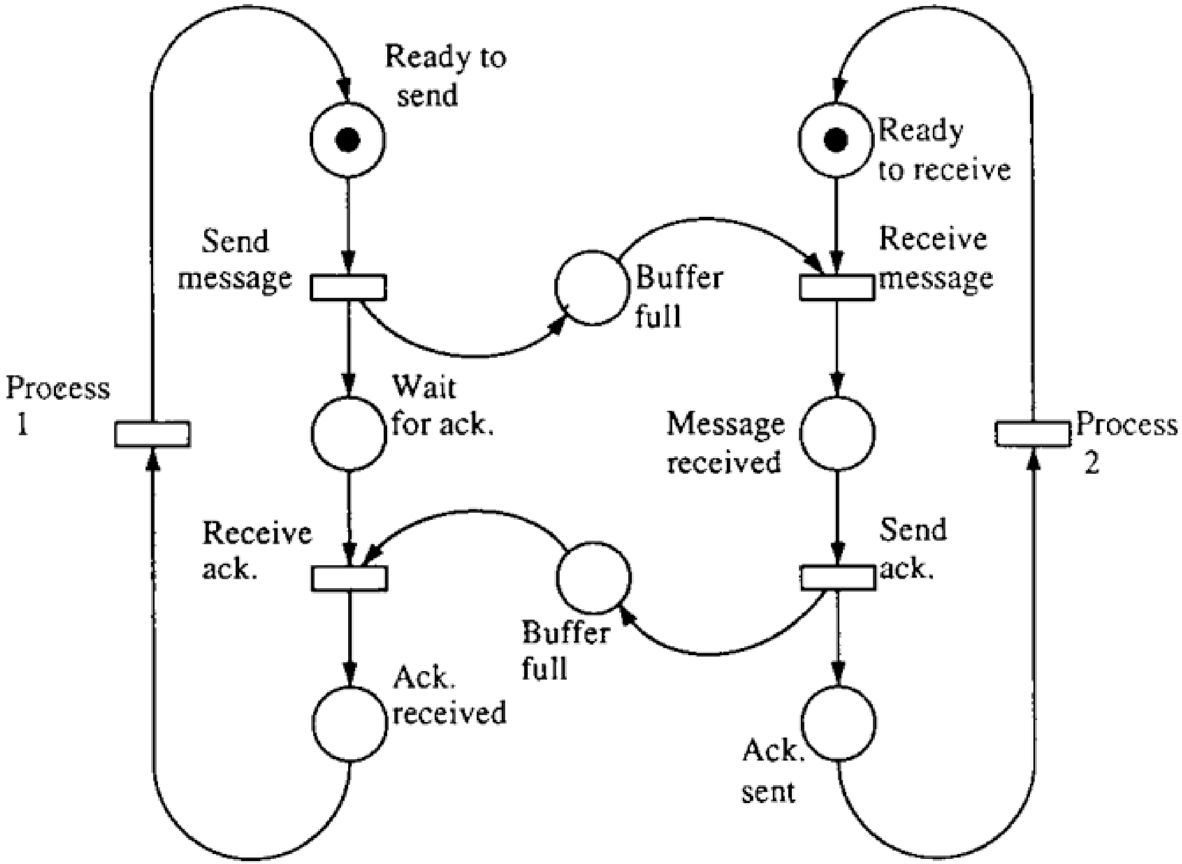




- b action of process Q can be executed after the execution of action a of process P

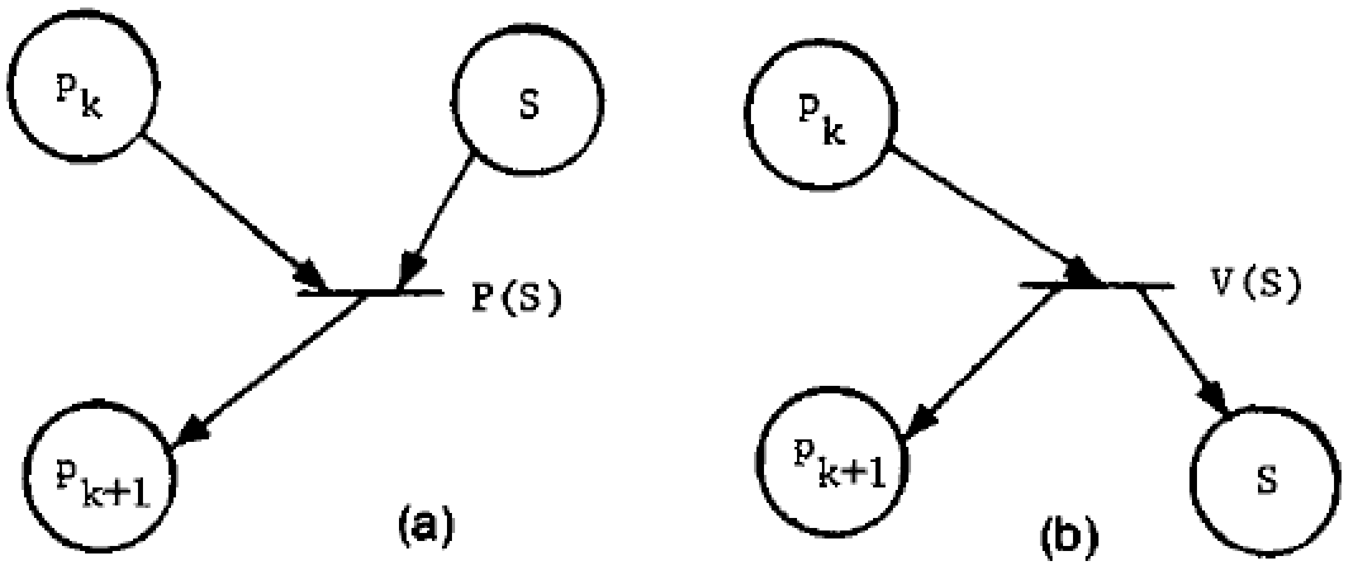
- b action of process Q and a action of process P must be executed synchrounously

COMMUNICATION

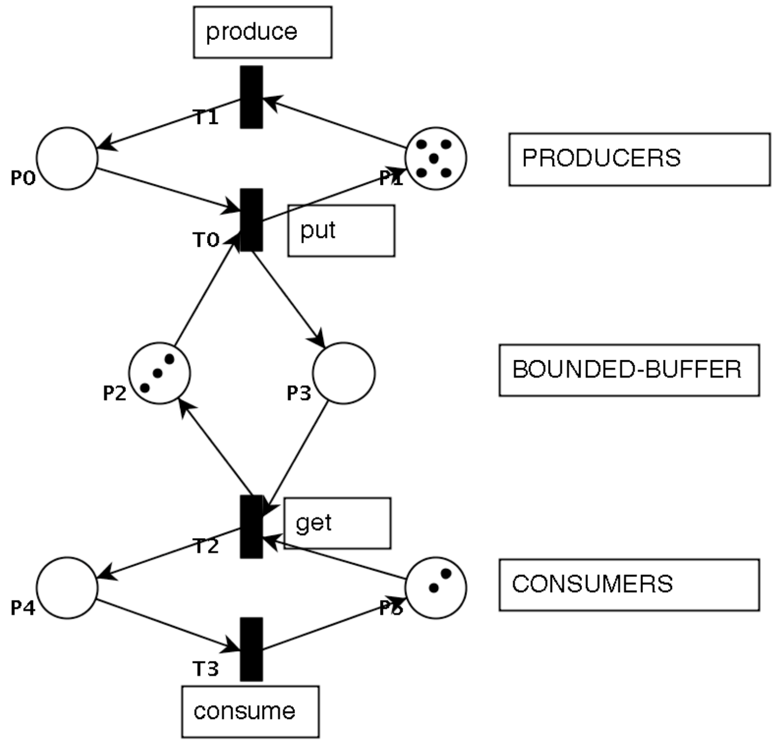


SEMAPHORES

- Semaphore modeled as a shared resource (place)
  - modelling wait (P) as a transition with the semaphore res. as input place
  - modelling signal (Q) as a transition with the semaphore res. as output place

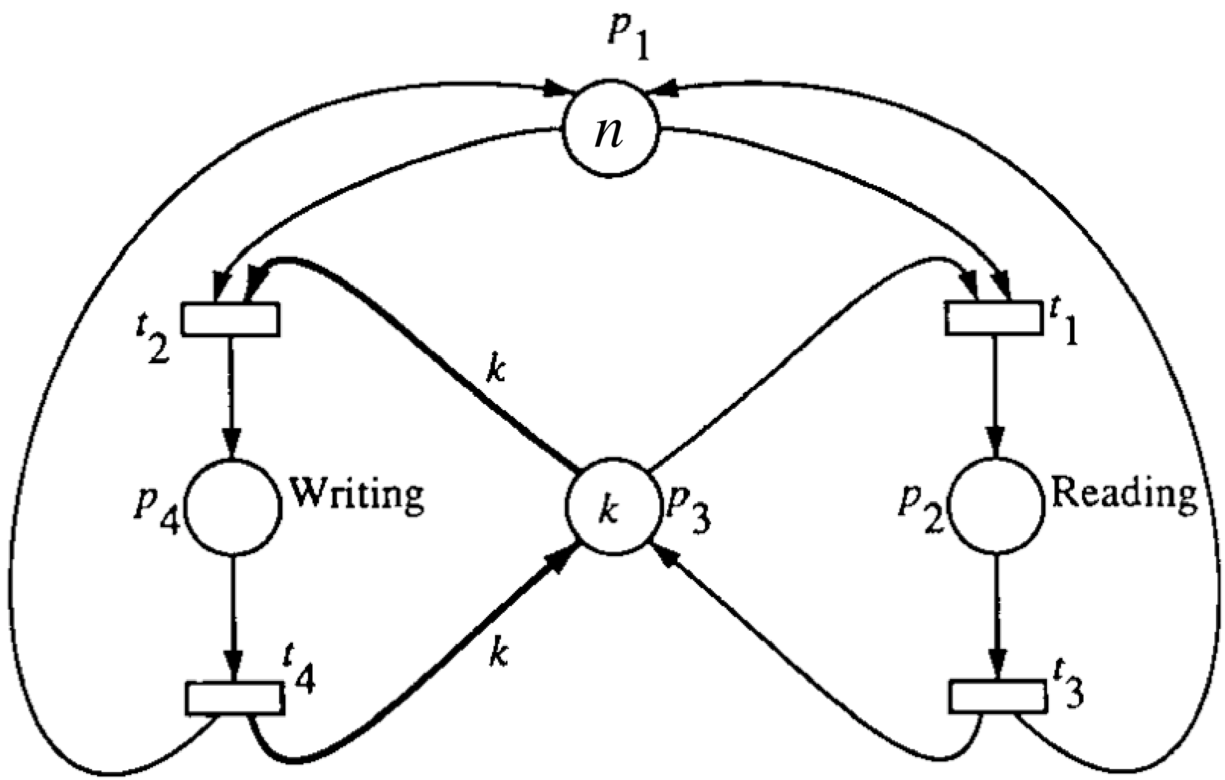


PRODUCERS AND CONSUMERS



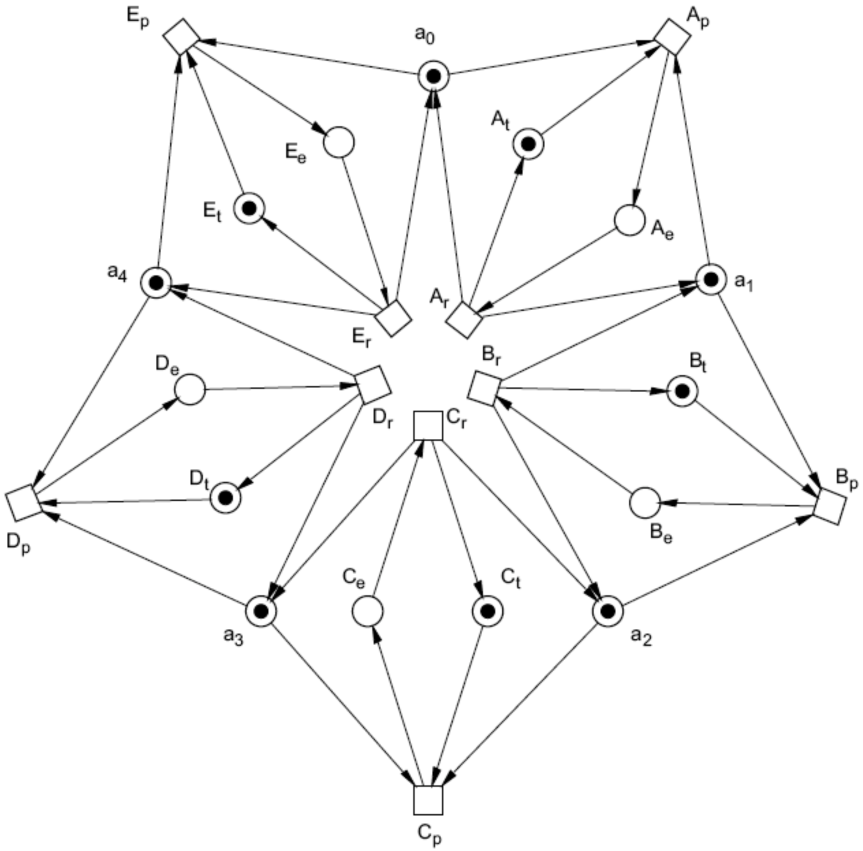
READERS-WRITERS

- The n tokens in p1 represent n processes that may want to read or write a shared memory represented by p3



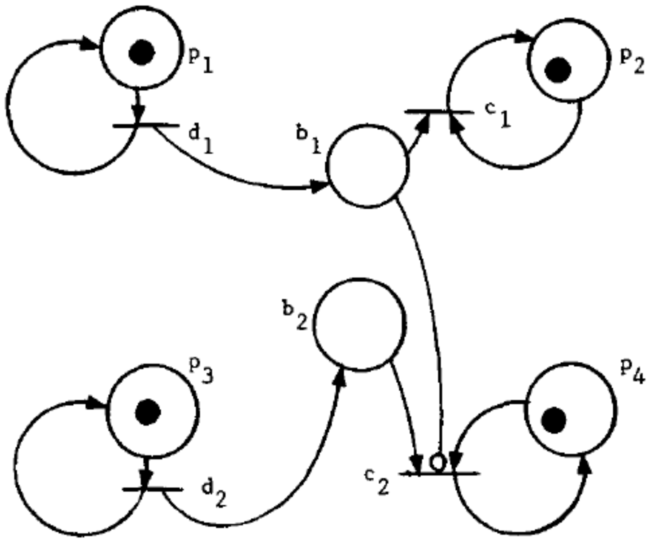
DINING PHILOSOPHERS

- Forks are represented by places *ai*
- Philosophers thinking by A*t*,B*t*,C*t*,D*t*,E*t* places and eating by A*e*,B*e*,C*e*,D*e*,E*e* places



EXTENDED PETRI NETS WITH INHIBITOR ARCS

- Zero-testing extension
  - extending the basic PN with the possibility of firing a transition only if a certain place has zero tokens
    - *inhibitor arc* represented by an arc with a small circle at the end



  - PN+inhibitor arc = Turing-equivalent
    - expressiveness and undecidability problems

FORMAL DESCRIPTION OF PETRI NETS

- PN can be formally described so as to enable a rigourous analisys of properties and problems of the system modeled
  - **structural** properties
    - independent from the initial marking
  - **behavioural** properties
    - dependent on the marking
- Mapping correctness of the systems on to structural / behavioural properties of the nets
  - safety and liveness properties

PETRI NET STRUCTURE

- The structure of a Petri Net can be formally described as a tuple

$$C = (P, T, I, O)$$

  - P is a set of places
  - T is a set of transitions
  - input function I defines the set of *input* places for each transition t_j
  - output function O defines the set of *output* places for each transition t_j

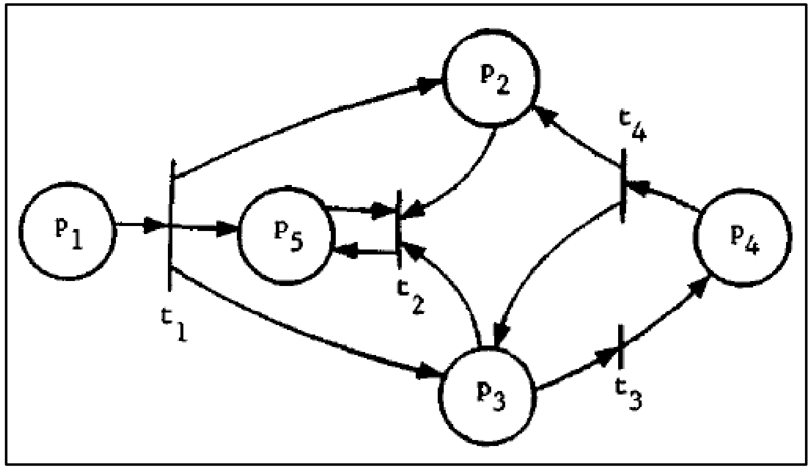
EXAMPLE

```
P = { p1, p2, p3, p4, p5 }
T = { t1, t2, t3, t4 }

I(t1) = {p1}
I(t2) = {p2,p3,p5}
I(t3) = {p3}
I(t4) = {p4}

O(t1) = {p2,p3,p5}
O(t2) = {p5}
O(t3) = {p4}
O(t4) = {p2,p3}
```

Corresponding Petri-Net graph:



MARKING

- A **marking** is an assignement of tokens to the places of the net
- Can be formally represented either as
  - a vector of N elements, one for each place, representing the number of tokens for each place
  - a function $\mu : P \rightarrow N$
    - $\mu(p_i)$ is the number of tokens in the place pi
- A marked Petri Net is represented by 5-tuple: $M = (P, T, I, O, \mu)$

EXECUTION RULE SEMANTICS

- The *state* of a Petri Net is defined by is marking
  - firing of a transition represents a change in a the state of the net.
- Next-State partial function $\delta(\mu, t_j)$
  - the function is undefined if the transition is not enabled in the marking
  - if tj is enabled $\mu' = \delta(\mu, t_j)$ is the marking that results from removing tokens from the input of tj and adding tokens to the output of tj.
- Given a PN and an initial marking, we can execute the PN by successive transition firings
  - firing a transition tj in the initial marking produces a new marking $\mu^1 = \delta(\mu^0, t_j)$
  - in this new marking we can fire any new enabled transition, say tk, resulting in a new marking $\mu^2 = \delta(\mu^1, t_k)$
  - this can continue as long as there is at least one enabled transition in each marking
  - if we reach a marking in which no transition is enabled, then no transition can fire and the PN must stop
- Non determinism
  - multiple sequence of markings $(\mu^0, \mu^1, \mu^2, ...)$ and related transitions $(t_j^0, t_j^1, t_j^2, ...)$ can result by executing a PN

REACHABILITY SET

- Immediately reachable marking
  - a marking mu' is *immediately reachable* from mu if we can fire some enabled transition in mu resulting in mu'
- *Reachable marking*
  - a marking mu' is *reachable* from mu if it is immediately reachable from mu or is reachable from any marking mu’’ which is immediately reachable from mu
- *Reachability set* of a PN
  - set of all states into which the PN can enter by any possible execution

ANALYSIS OF PN MODELS

- *Safe* nets
  - Petri nets in which no more than one token can ever be in any place of the net at the same time.
  - Justification based on the original definition of events and conditions
    - a condition is represented by a place.
    - the fact that the condition holds is indicated by a token in the place
    - so a token should be either present or not: more than 2 token is pointless
- *Bounded* net or k-bounded net (boundness)
  - Nets in which the number of tokens in any place is bounded by k
  - safe nets are 1-bounded net
  - Boundedness is a very important practical property:
- *Conservative* net
  - PN is conservative if the number of tokens in the net is conserved.
  - think for instance of using tokens to represent resources..

LIVENESS

- Based on transition analysis
  - dead transition in a marking
    - if there is no sequence of transition firings that can enable it
    - related to deadlock situations
  - potentially firable
    - if there exists some sequence that enables it
    - related to starvation situation
  - live transition
    - if it is potentially firable in all reachable markings
- For liveness, it is important not only that a transition be firable in a given marking, but staying potentially firable in all markings reachable from that marking
  - if it is not true, then it is possible to reach a state in which the transition is dead
    - deadlocks

PETRI NET EXTENSIONS

- *Timed* Nets
  - introducing time delays associated with transitions and/or places
    - useful for performance evaluation and scheduling problems
  - deterministic timed nets
    - delay are deterministically given
  - stochastic nets
    - delays are probabilistically specified
- *High-level* Nets
  - associate some kind of symbolic / numerical information to tokens and some computational rules to transition consuming and producing tokens
    - Coloured Petri Nets, Predicate Transitions Nets
  - **Coloured Petri Nets**
    - assigning typed values (“a color”) to each token

PETRI NET TOOLS

- Many tools available for creating and analysing Petri Nets
  - check http://www.informatik.uni-hamburg.de/TGI/PetriNets/
- An example: PIPE 2
  - Platform Independent Petri net Editor 2
  - Java-based, open-source: http://pipe2.sourceforge.net/

STATECHARTS

STATECHARTS

- Introduced by David Harel in 1987 for modelling *complex reactive systems*
  - now part of UML with the name of state diagrams
- Reactive systems
  - systems being, to a large extent, *event-driven*, continuosly having to react to external and internal stimuli
    - examples include automobiles, communication networks, operating systems, avionic systems, man-machine interface of many ordinary software
  - contrast to *transformational* systems
    - input / output, data-processing systems
- Main objective
  - introducing a way of describing reactive behaviour that is clear and realistic, and at the same time formal and rigorous
    - to be simulated and analyzed

BEYOND BASIC STATE DIAGRAMS

- General agreement that **states** and **events** are a rather natural medium for describing the dynamic behaviour of a complex systems
  - state transition: "when event alfa occurs in state A, if condition C is true at that time, the system tranfers to state B"
- But finite state machine and state transition diagrams don’t scale with complexity
  - unmanageable, exponentially growing moltitude of states, all of which have to be arranged in a "flat" unstratified manner
  - lead to unstructured, unrealistic and chaotic state diagram
- To be useful a state/event approach must be *modular*, *hierarchical* and *well-structured*
  - it must solve the exponential blow-up problem, by somehow relaxing the requirement that all cobinations of stateshave to be represented explicitly
- Statecharts proposal
  - extension of conventional state diagrams by mechanisms to enhance the descriptive power

STATECHARTS FORMALISM

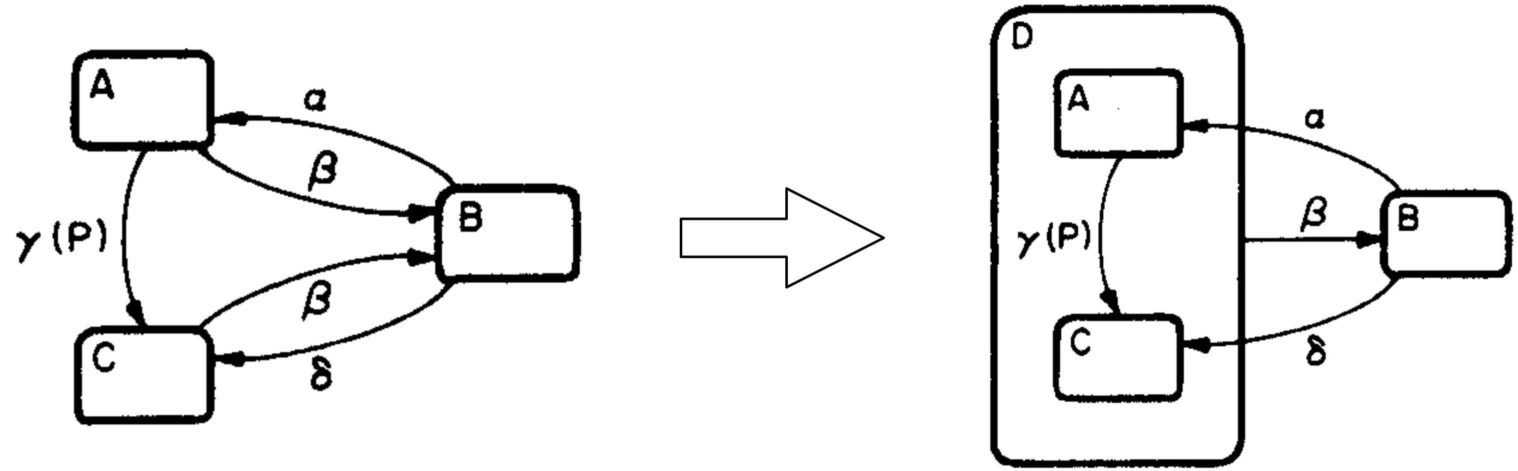
- Visual formalism to describe states and transitions in a modular fashion
  - **hierarchy**
    - clustering
    - refinement
    - promoting 'zoom' capabilities for moving easily back and forth between levels of abstractions
  - **orthogonality**
    - independence / concurrency of substates
    - synchronization among substates

STATE AND EVENTS IN STATECHARTS

- States and events
  - boxes (rounded rectangle) denotates states
  - arrows labelled with event
    - optionally with a parenthesized conditions and an action (described later on)
- Different state levels (= hierarchy support)
  - encapsulation express hierarchies
  - arrows can originate and terminate at any level

HIERARCHY: CLUSTERING

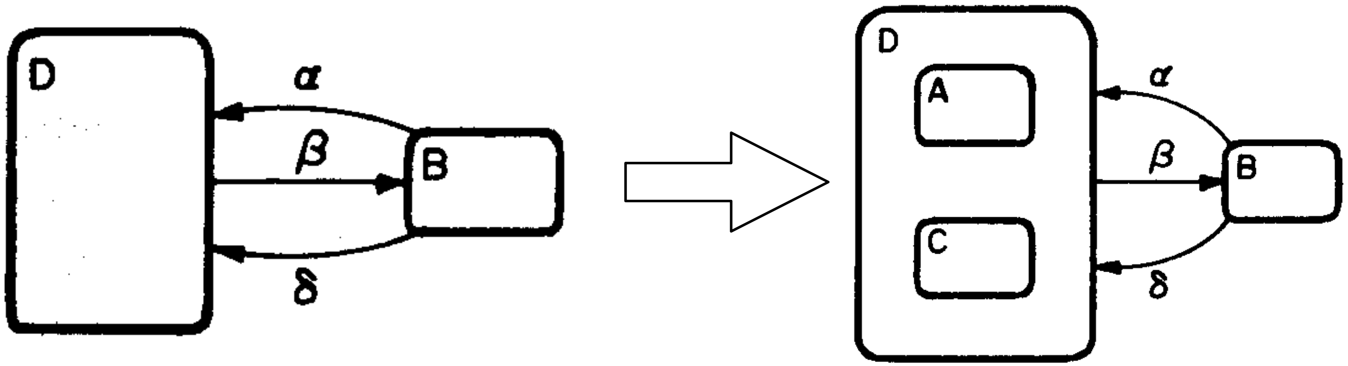
- XOR Decomposition
  - economizing arrows



- since beta takes the system to B from either A or C, we can cluster the latter into a new super-state D and replace the two arrows by one
  - the semantics of D is a XOR of A and C: to be in state D one must be either in A or in C, and not in both.
  - D is an *abstraction* of A and C
    - capturing common properties
- bottom-up approach

REFINEMENT

- We can proceed on the opposite direction, refining states:

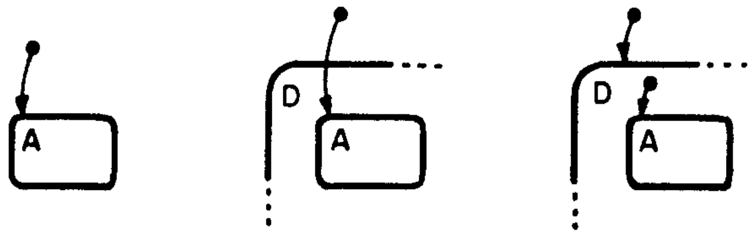


  - in this case the incoming alfa and beta arrows are underspecified
- top-down approach

- Zooming in and out support
  - zooming-in
    - by looking inside a state
  - zooming-out
    - abstracting from the inside of a state

DEFAULT STATES

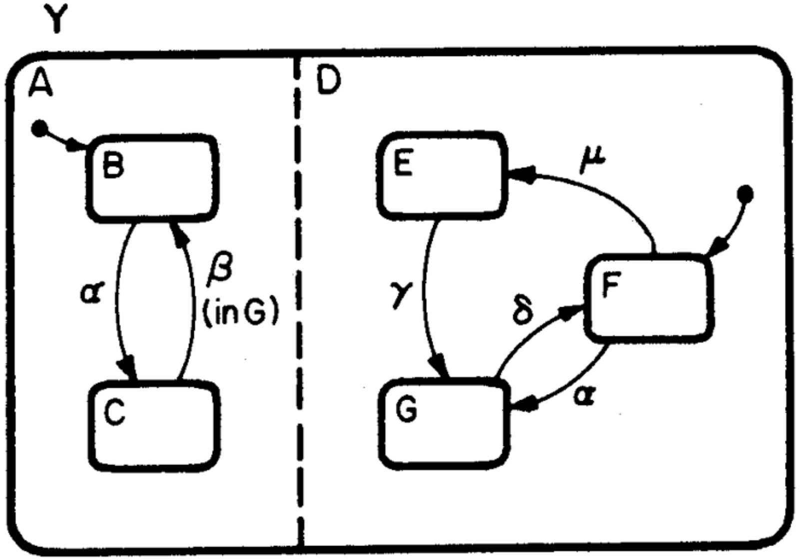
- Special arrow to explicitly represent the default entering state
  - at any level



- Take into the account the history
  - entering the state most recently visited
  - H default-state arrows

HIERARCHY 2: ORTHOGONALITY

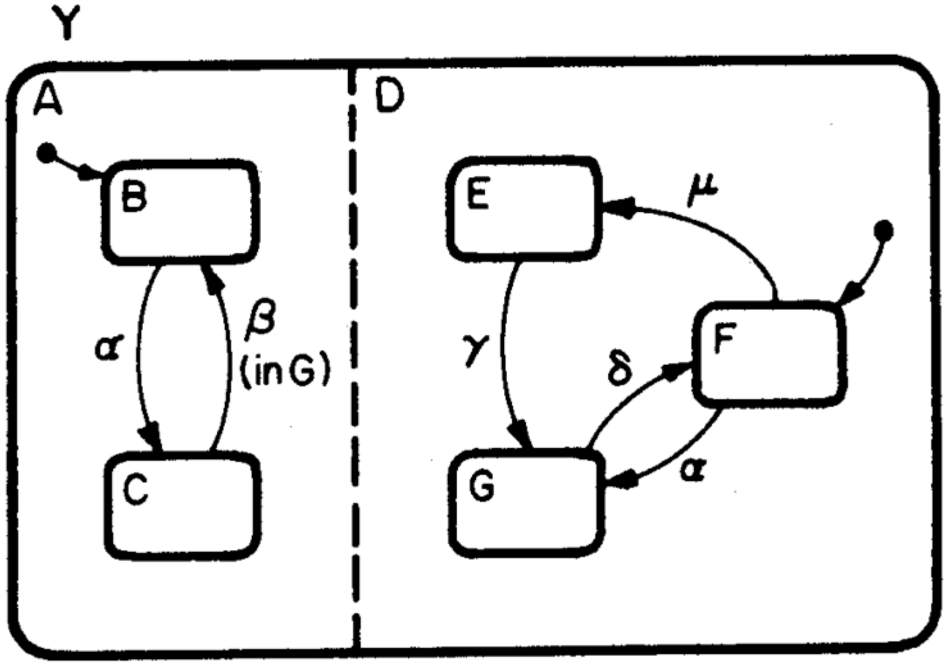
- AND decomposition
  - capturing the property that, being in a state, the system must be in all of its AND components
  - the notation used in statecharts is the physical splitting of a box into component using dashed lines



  - state Y consists of AND components A and D
    - with the property that being in Y entails being in some combination of B or C with E, F or G.
    - Y is the orthogonal product of A and D
  - Independency and / or Concurrency

SYNCHRONIZATION

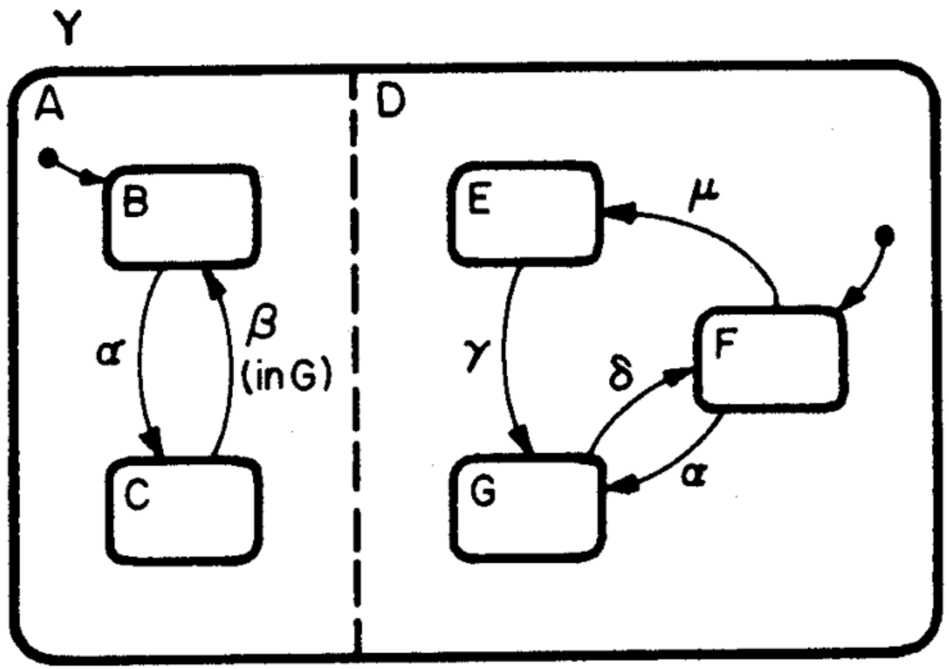
- In the example, if an event alfa occurs, it transfers B to C and F to G simultaneously, resulting in a new combined state (C,G)



- This illustrates a certain kind of synchronization
  - a single event causing simultaneous happenings

INDEPENDENCE

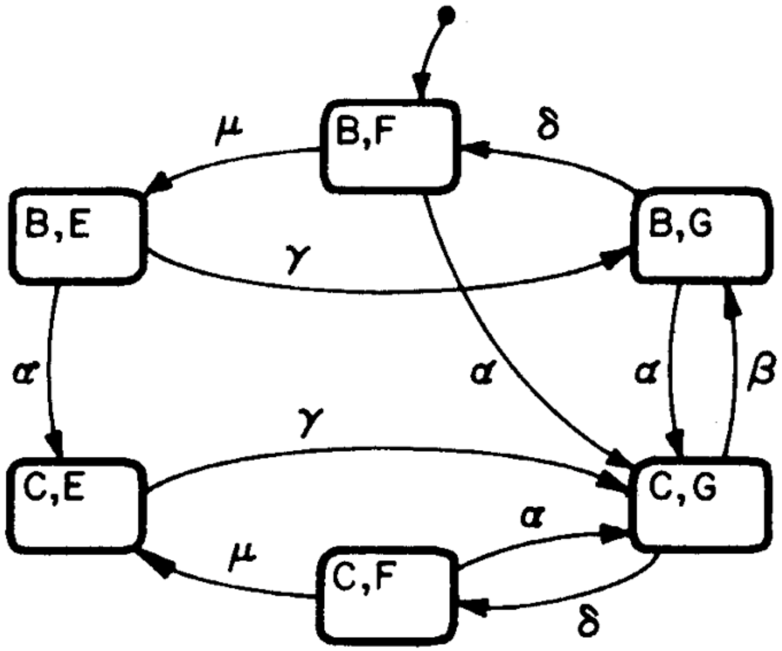
- On the other hand, mu occurs at (B,F) it affects only the D component, resulting in (B,E)



- This illustrates a certain kind of independence
  – the transition is the same whether the system is in B or C in its A components

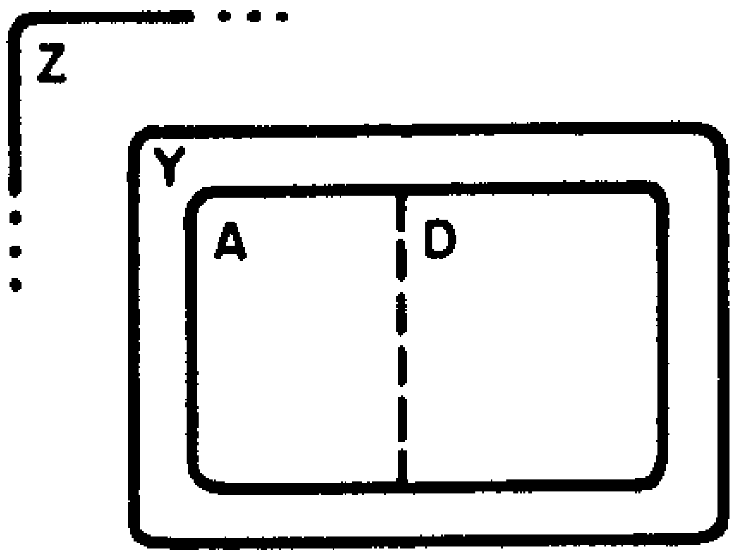
AND-FREE EQUIVALENT

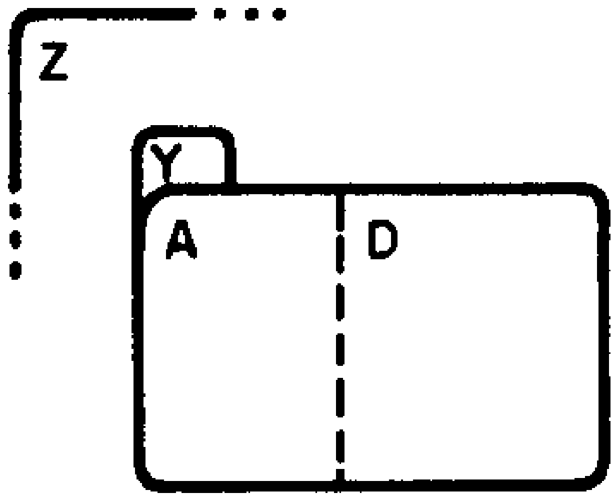
- The AND-Free equivalent diagram has the product of the states



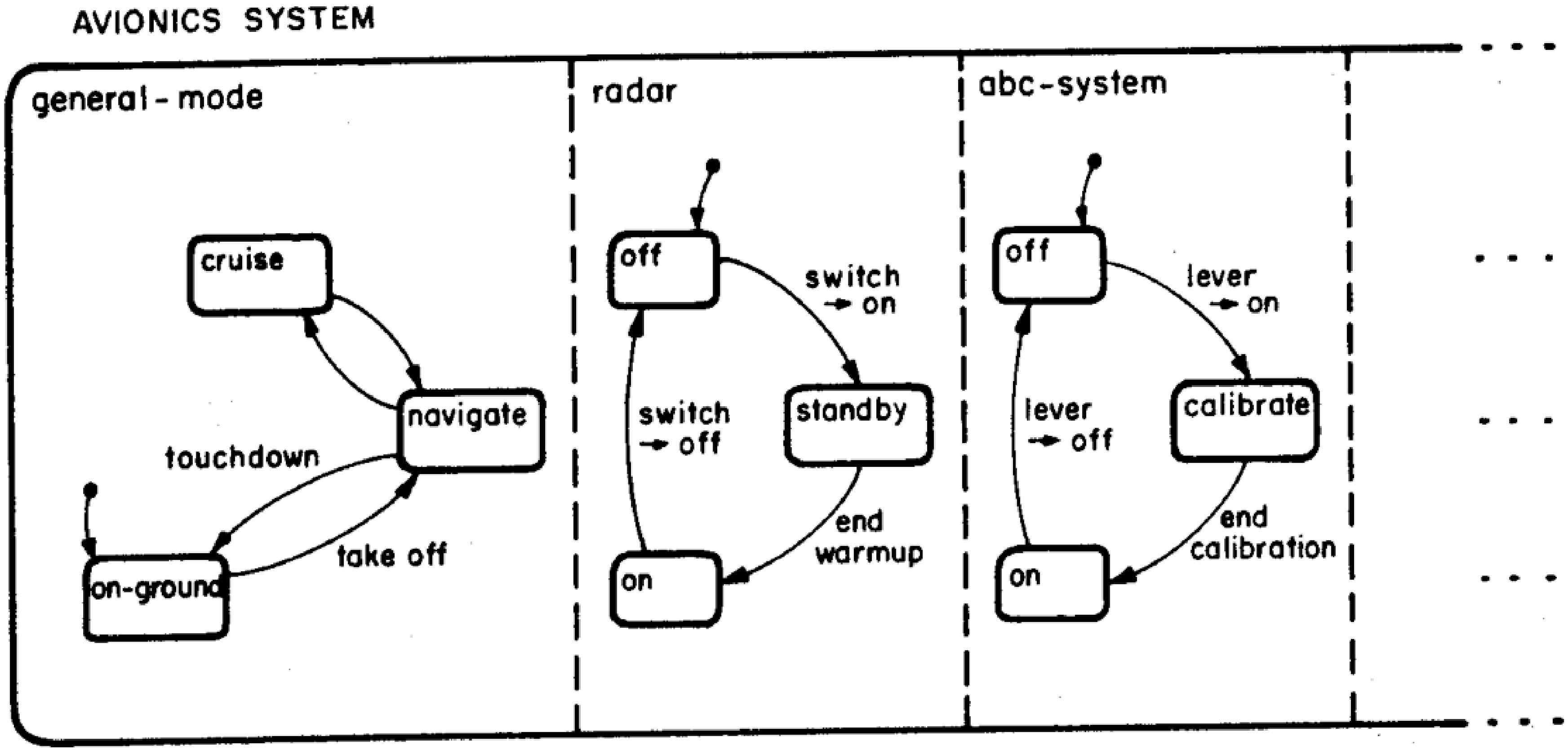
- That is: if we have two components with 1000 states, we have one million of states in the product
  - if we have 3 components: 10^9 states..

NOTATIONS FOR AND-DECOMPOSITION



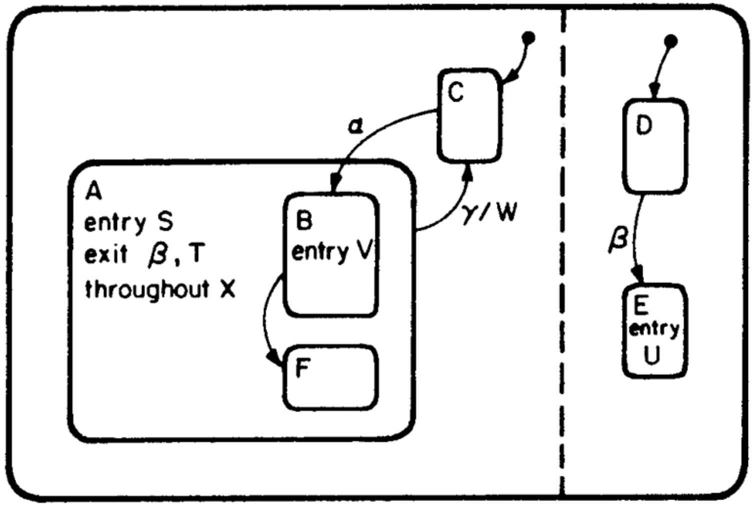


AN EXAMPLE


AVIONICS SYSTEM
general - mode
radar
abc-system
cruise
navigate
touchdown
take off
on-ground
off
switch → on
standby
switch → off
end warmup
on
off
lever → on
calibrate
lever → off
end calibration
on

ACTIONS

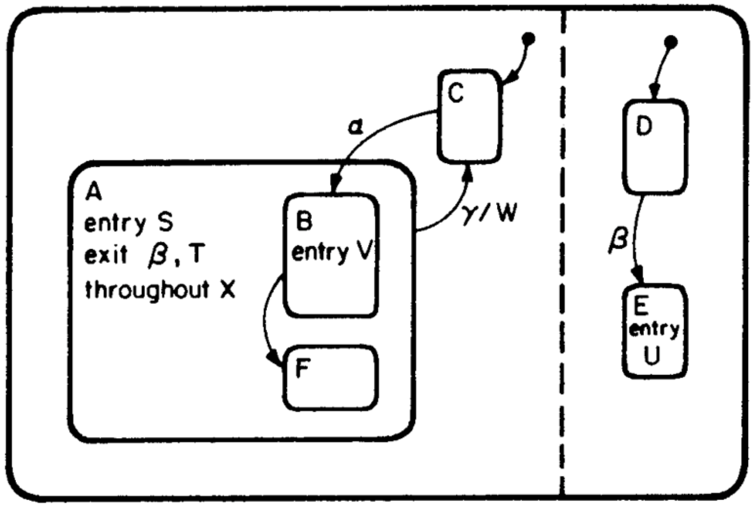
- Actions represents the ability of the statecharts to generate events and to change the value of conditions
  - influencing other components of the system
  - influencing the environment of the system



- Expressed by the notation ".../S" that can be attached to the label of the transition
  - S is an action carried out by the system
  - actions have instantaneous occurrences that take ideally 0 time.

ACTIVITIES

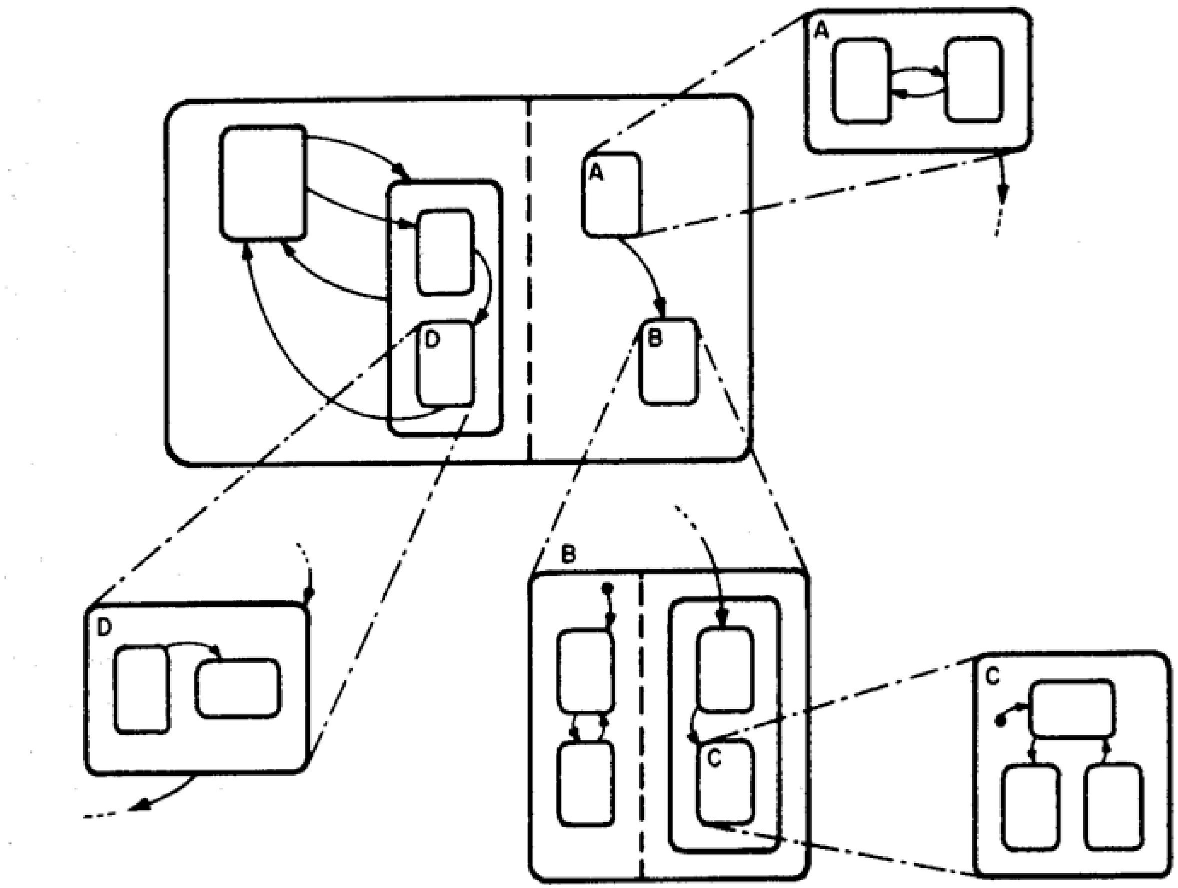
- Activities
  - are to actions what conditions are to events
  - an activity always takes a nonzero amount of time (like beeping, displaying, executing lengthy compytations..)
  - activities are durable



- Activities are associated with states
  - entry and exit actions

FURTHER FEATURES: UNCLUSTERING

- Laying out parts outside the natural neighborhood



THE STATEMATE TOOL

- Statemate is a comprehensive graphical modeling and simulation tool for the rapid development of complex embedded systems based on statecharts
  - using a combination of traditional graphical design notations combined with some of the Unified Modeling Language (UML) diagrams
- Statemate provides a direct and formal link between user requirements and software implementation by allowing the user to create a complete, executable specification
  - this specification may be executed, or graphically simulated, so the system engineer can explore what-if scenarios to determine if the behavior and the interactions between system elements are correct
  - these scenarios can be captured and included in Test Plans which are later run on the embedded system to ensure that what gets built meets what was specified.
  - this executable specification is also used to communicate with the customer or end user to confirm that the specification meets their requirements

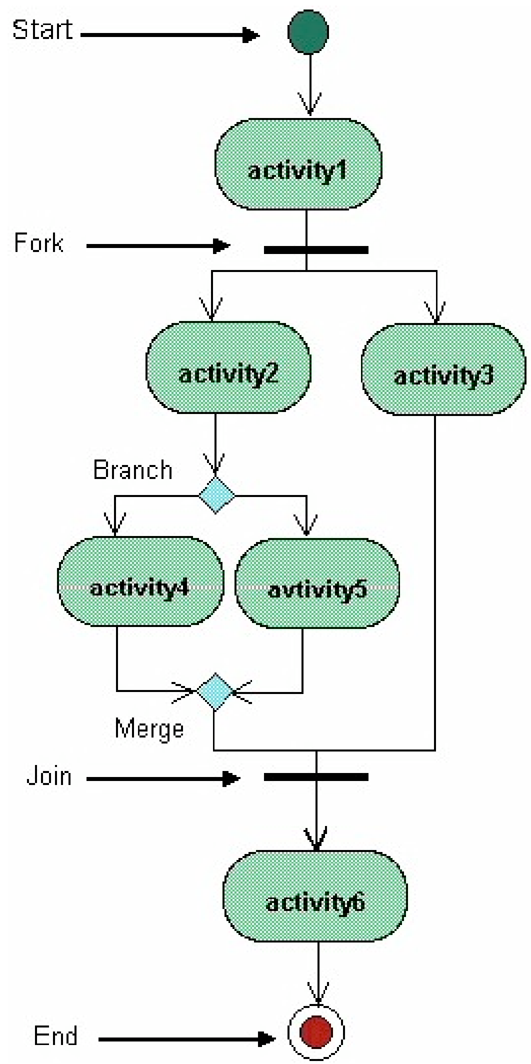
ACTIVITY DIAGRAMS

ACTIVITY DIAGRAMS

- Activity diagrams are one of the diagrams adopted in UML to represent the business and operational workflows of software system
  - an activity diagram is a dynamic diagram that shows the activity and the event that causes the object to be in the particular state
- Activity diagrams vs. state diagrams
  - a state diagram shows the different states an object is in during the lifecycle of its existence in the system, and the transitions in the states of the objects
    - these transitions depict the activities causing these transitions, shown by arrows
  - an activity diagram talks more about these transitions and activities causing the changes in the object states

ACTIVITY DIAGRAM OVERVIEW (*)

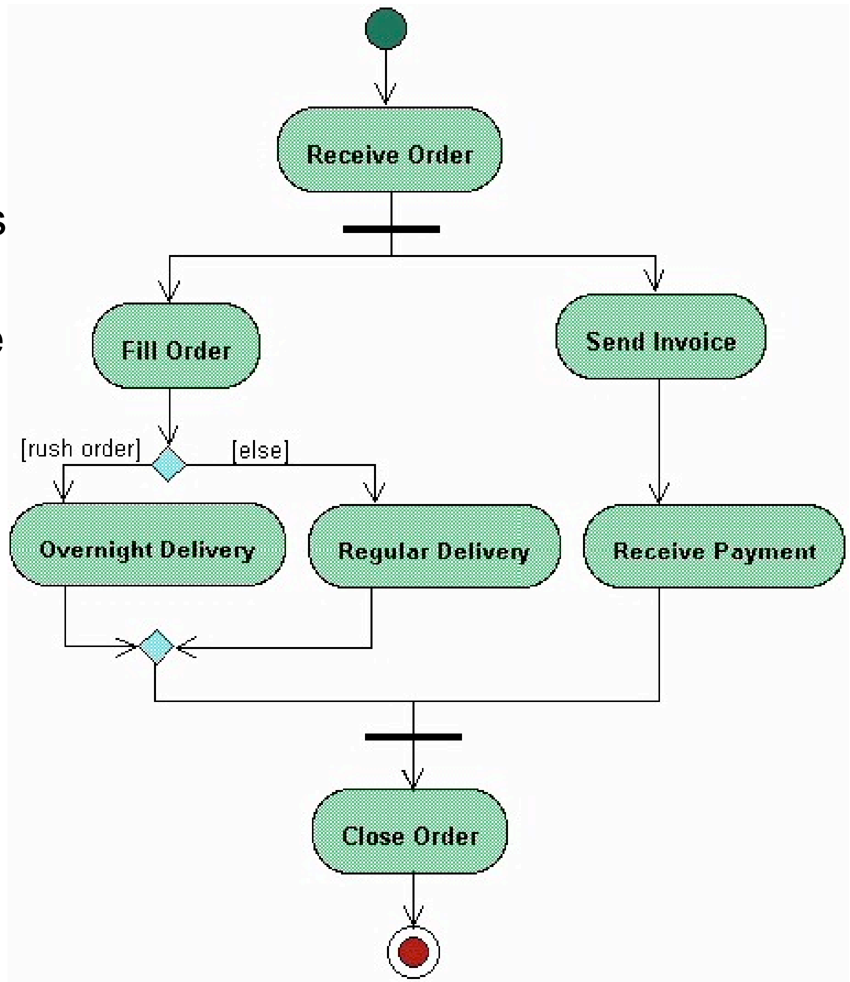
- Showing the flow of activities through the system
  – diagrams are read from top to bottom and have branches and forks to describe conditions and parallel activities. A fork is used when multiple activities are occurring at the same time.
- The diagram below shows a fork after activity1
  – this indicates that both activity2 and activity3 are occurring at the same time. After activity2 there is a branch. The branch describes what activities will take place based on a set of conditions. All branches at some point are followed by a merge to indicate the end of the conditional behavior started by that branch. After the merge all of the parallel activities must be combined by a join before transitioning into the final activity state.



(*) taken from http://atlas.kennesaw.edu/~dbraun/csis4650/A&D/UML_tutorial/activity.htm

PROCESSING ORDER EXAMPLE (*)

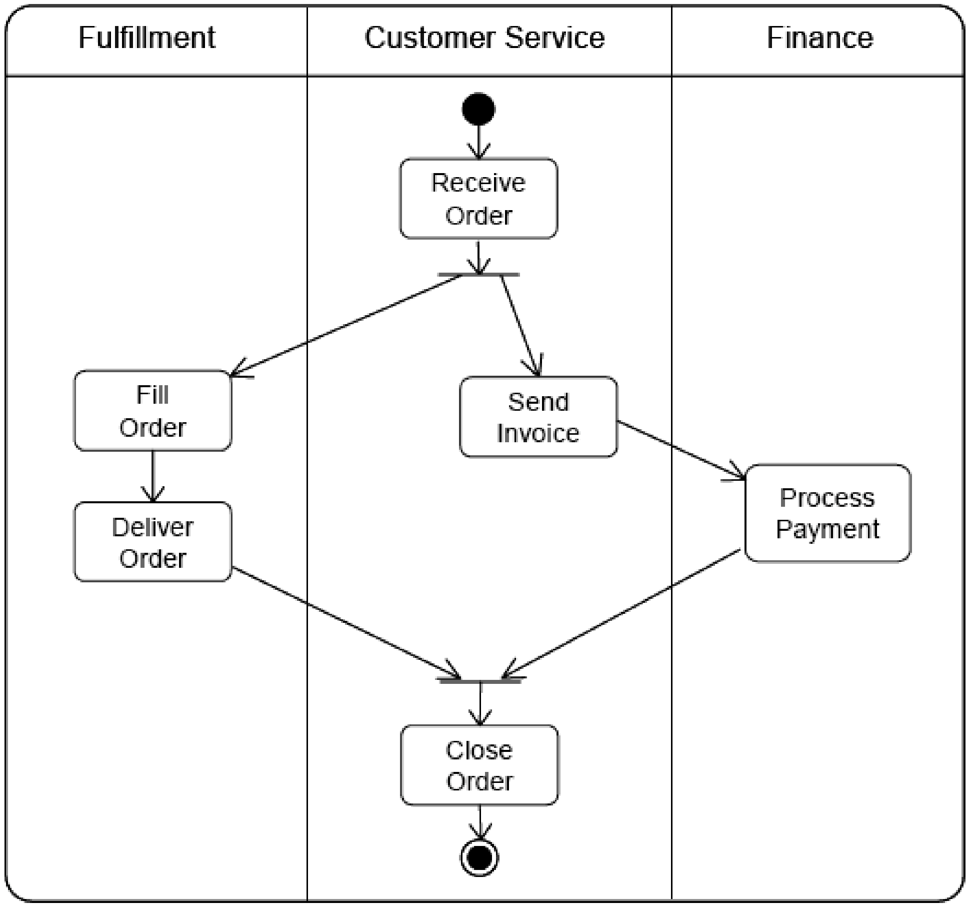
- The diagram shows the flow of actions in the system's workflow
  - once the order is received the activities split into two parallel sets of activities
  - one side fills and sends the order while the other handles the billing
  - on the Fill Order side, the method of delivery is decided conditionally.
  - depending on the condition either the Overnight Delivery activity or the Regular Delivery activity is performed.
  - finally the parallel activities combine to close the order.



(*) taken from http://atlas.kennesaw.edu/~dbraun/csis4650/A&D/UML_tutorial/activity.htm

SWIMLANES

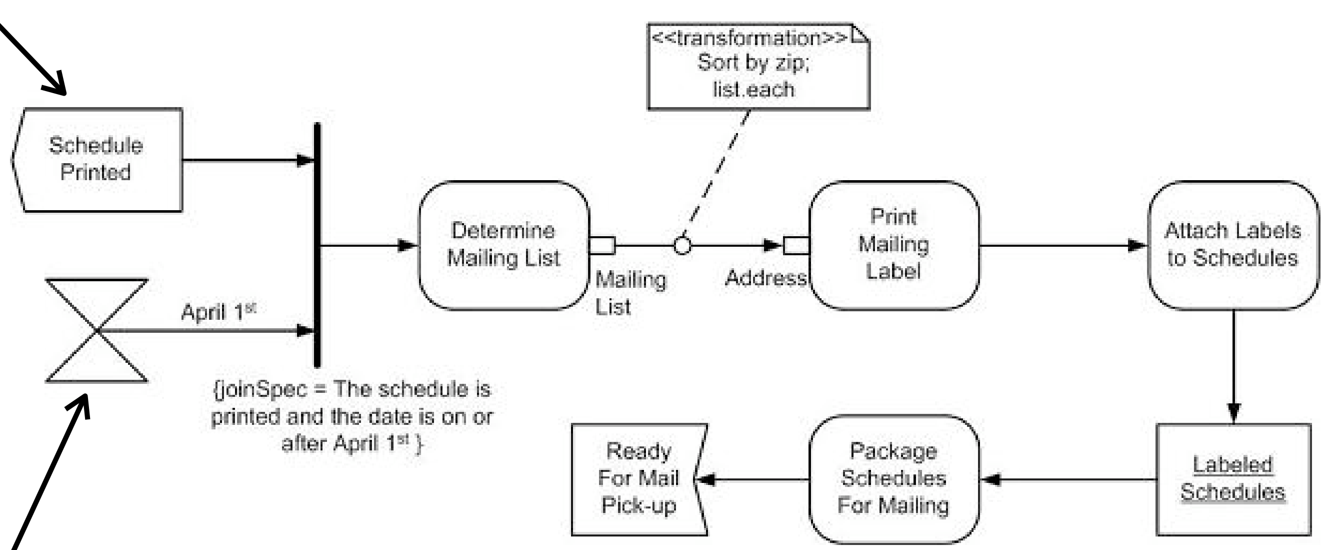
- A swimlane is a way to group activities performed by the same actor on an activity diagram or to group activities in a single thread



SIGNALS

- *Signal* Activities
  - activities that send or receive messages (output / input signals)
- Triggers
  - temportal signals

input signal

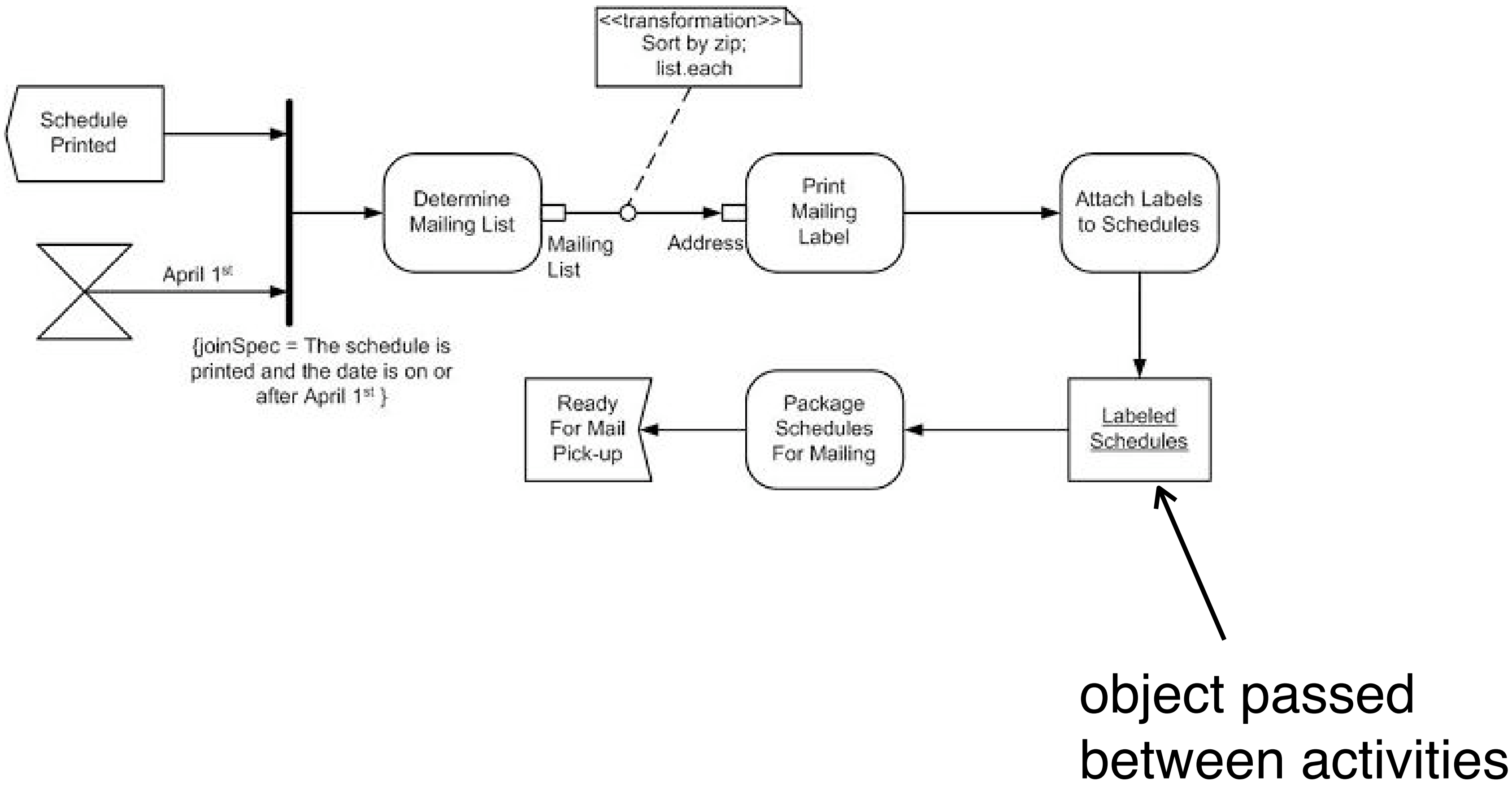


time trigger

output signal

PASSING OBJECTS

- Specifying objects passed between activities



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