Statemate Course

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Introduction to Statecharts

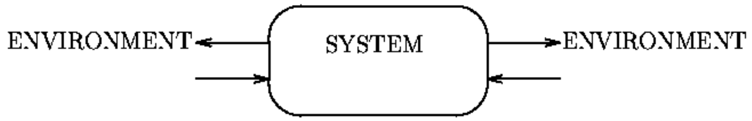
Everything you wanted to know about Statecharts
but were afraid to ask

Abstract: The notion of a reactive system and the language Statecharts are introduced. The rationale behind the design decisions of Statecharts is explained in relation to the specific nature of reactive systems.

Literature: Introduction to Design Choices in the Semantics of Statecharts, C. Huizing, W.-P. de Roever, Information Processing Letters 37, p. 205-213, 1991

What is a system?

A composed and relative independent whole that can exchange (material, energy, information) with its environment.



The two essential elements in this definition are:

1. group of components, that form a connected whole
2. the exchange with its environment.

How to Characterize Systems?

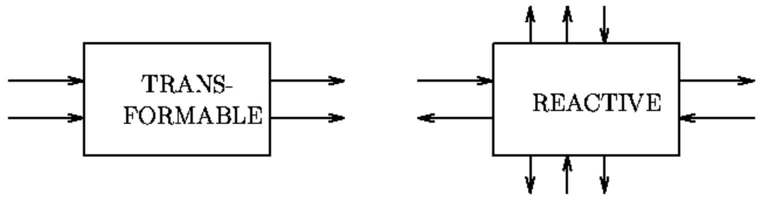
The systems are often divided in two categories that make distinction between more simple and more difficult systems.
Examples of this separation are:

- sequential versus parallel,
- central versus distributed,
- deterministic versus nondeterministic,
- terminating versus nonterminating.

Another Separation

There is another separation, namely:

- **transformational** and
- **reactive systems**.



Transformational systems

are described by the relation between initial and corresponding final states; they have a linear structure, because only the initial and corresponding final states are of interest.

Examples include: sorting algorithms, compilers, and other algorithms computing a function as discussed in your data structures and complexity of algorithms course.

Reactive systems

do not compute a function, but are in continuous **interaction** with their environment.

Examples: your tv set, digital watches, chips, interactive software systems, game programs s.a. trackman, monkey island, tomb raider, and other interactive computer games, but also one's heart monitor at an intensive care unit.

Why use Formal Methods?

- in the formalization process ambiguities, omissions and contradictions can be found in the informal formulation of the problem,
- the formal model can be proven correct with mathematical methods,
- a formal specified system can be analyzed to have or to have not some wanted properties,
- a formal verified subsystem can be embedded in a greater system with more confidence,
- the formal model leads to (partly) automated development methods and tools like simulators,
- several designs can be compared with each other.

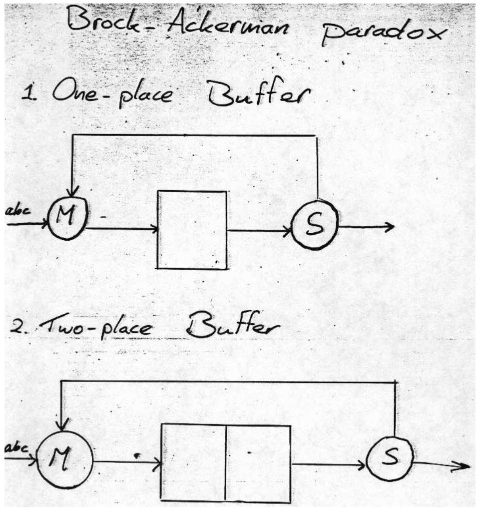
Transformational/Reactive Systems

- Transformational systems are well-studied; for their programming and analysis many good languages and theories exist.
- We explain why the language Statecharts is a good candidate for **specifying** and **programming** reactive systems.

Why not use transformational techniques?

- If transformational systems are so well studied, why doesn't one consider a reactive system as a transformational one?
  Simply say that a reactive system transforms a **sequence** of inputs to a sequence of outputs.
- This doesn't work, because of "feedback", as illustrated by the **Brock-Ackermann** paradox.
- Consider two systems, a one-place buffer and a two-place buffer. If you consider these transformationally, they display the same initial-final state behavior.

Brock-Ackermann paradox



in: $abc\ldots$
out: 1. e.g. $abac\ldots$
2. e.g. $abca\ldots$
not $abac\ldots$

Conclusion

If the output of these systems is fed back, and merged with their input they behave differently.

The relative order of output events relative to the input events needs to be specified, in order to characterize the semantics of a system with interaction with its environment through feedback.

(One needs to know when an output is produced)

Initial/Final State Behavior

Transformational systems have a linear structure, and so have the conventional languages for specifying and programming them. What one describes is how a final state is produced from an initial one. **The relative time when intermediate states are computed is not important**, and neither is their identity as long as the corresponding final state is known!

Reactive Behavior

- For reactive systems this is completely different:
  - The "moment" a new input arrives is relevant to the behavior of the system $\Longrightarrow$
  - The internal state of the system at the time of input is important for the systems reaction.
  - Reactive systems may not even have a final state!
- So, in reactive systems **there is no main sequential flow of control** (as in transformational systems) and **statements can have several entry and exit points.**

Finite State Machines

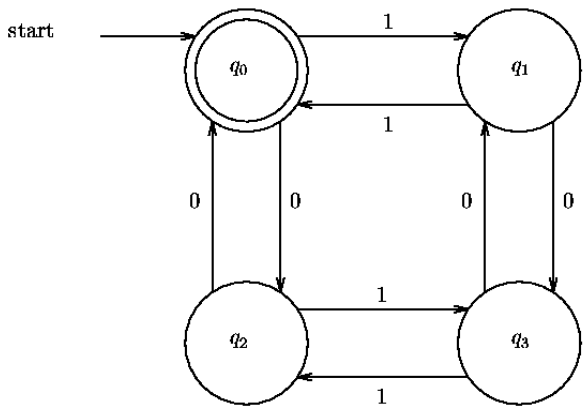
Finite Automata

Formally a *finite automaton* is defined as a five tuple $(Q, \Sigma, \delta, q_0, F)$ where

Q	is a finite set of states,
Σ	is the input alphabet,
$q_0 \in Q$	is the begin state,
$F \subseteq Q$	is the set of final states,
$\delta : Q \times \Sigma \to Q$	is the transition function.

The transition function gives for every state q and every input symbol a the new state $\delta(q, a)$ that arises as reaction on the execution of a in state q.

State Diagram



For each state, the possible reactions to input that arrives in that state is specified by a transition to other states.

Extensions

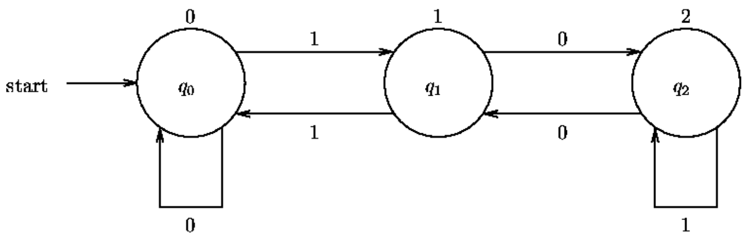
A restriction of these kind of automata as defined above is the fact that they have an input alphabet but not an output alphabet. There are two ways to extend the above model with output: output can be associated with a state (a so called Moore machine) or with a transition (a so called Mealy machine). These are formally defined as follows.

- A $Moore\ machine$ is a 6-tuple $(Q, \Sigma, \Delta, \delta, \lambda, q_0)$ where Q, Σ, δ, q_0 are the same as in the definition of the finite automaton,

Δ	is the $output\ alphabet$ and
$\delta : Q \to \Delta$	is the $output\ function$.

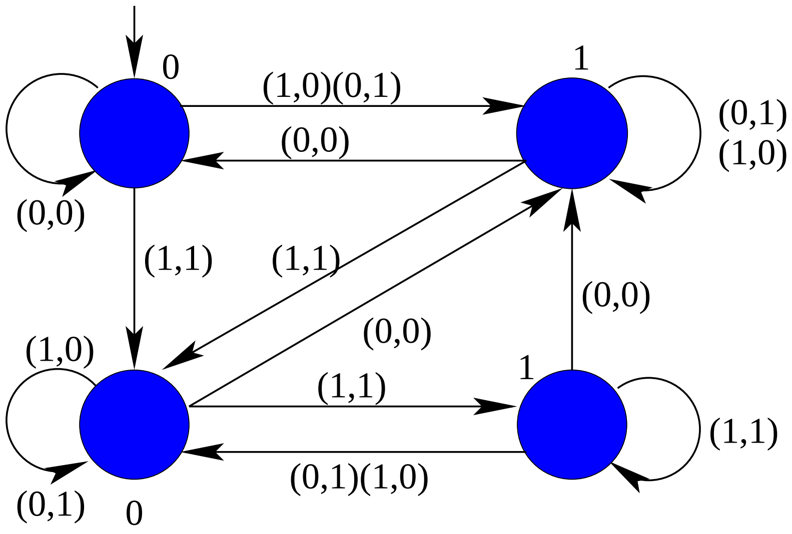
- A $Mealy\ machine$ is also a 6-tuple $(Q, \Sigma, \Delta, \delta, \lambda, q_0)$ but now λ is a function from $Q \times \Sigma$ to Δ.

Example: Moore Machine

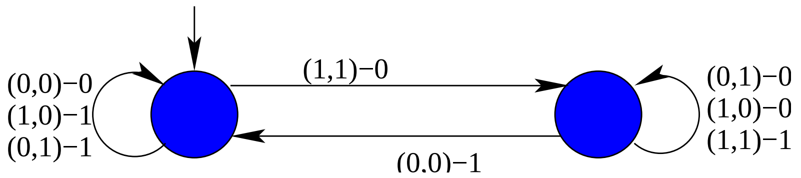


For a Moore machine λ the output is thus associated with every state, while for a Mealy machine $\lambda(q, a)$ gives the output associated with the transition of state q on input a.

Serial Addition: Moore Machine



Serial Addition: Mealy Machine

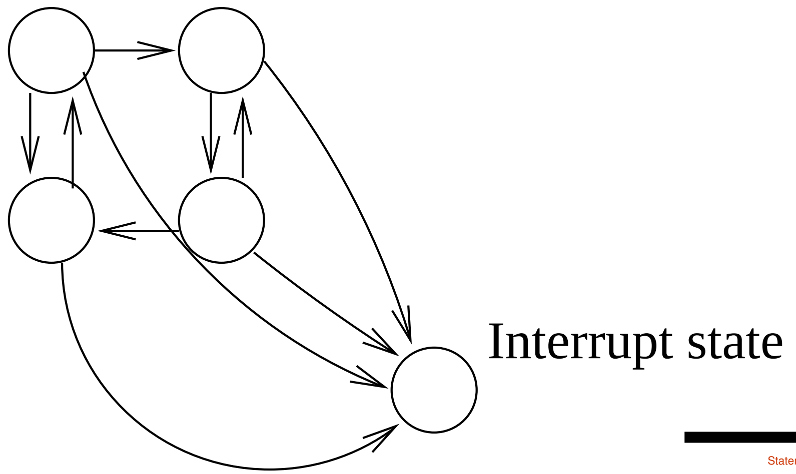


Disadvantages

- **They have no structure.** There is no strategy for their top-down or bottom-up development.
- state-transition diagrams are “flat”, i.e., without a natural notion of depth, hierarchy or modularity,
- state-transition diagrams are uneconomical concerning their transitions:think for instance of a high-level interrupt

Interrupt Transition

They are not economical w.r.t. transitions, when one event has all transitions as a starting point as in case of interrupts:



Disadvantages (cont’d)

- concerning the states state-transition diagrams are even very uneconomical: exponential blow-up
- They are not economical w.r.t. **parallel composition**: **Exponential growth** in the number of states when composed in parallel.
- the nature of state-transition diagrams is inherently sequential and so parallelism can‘t be represented in a natural way.

Statecharts

We need a formalism for the hierarchical development and refinement of Mealy machines.
This is provided by Statecharts, invented by David Harel.

Statecharts display **hierarchy** and **structure**, and enable hierarchical development.

Statecharts

Hierarchy and Structure

The concepts of hierarchy and structure in Statecharts are introduced using a quite familiar example of a reactive system: that of a **television set with remote control**.

First concept: Hierarchy

Hierarchy or depth in states, and interrupts. This is achieved by drawing states as boxes that contain other boxes as sub-states.

- The television set can be in two states: **on** and **standby**. Switching between them is done by pushing the **on** and **off** buttons, generating the **on** and **off** events:

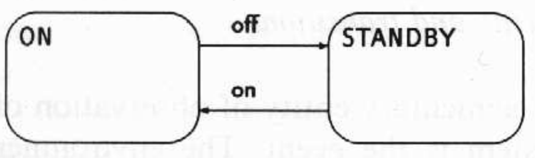


Fig. 2.

Zooming into ON

In state **on** the tv set can be in two sub-states: **normal** and **videotext**:

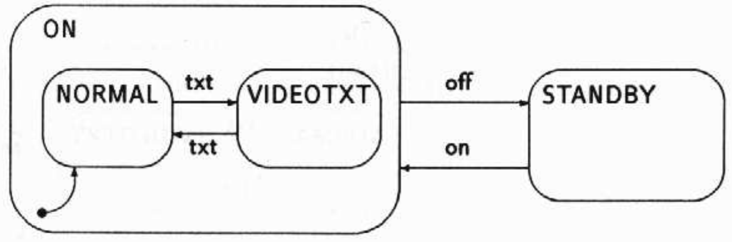


Fig. 3.

The $\longrightarrow$ arrow leading to **normal** specifies which sub-state should be entered when the higher level state**on** is entered, namely **normal**.

Superstates

When in **on** an event **off** is generated, this acts like an interrupt and state **on** (incl. all its sub-states) is left, and control switches to state **standby**. In this way interrupts are handled without cluttering the picture with arrows.

Second concept: Orthogonality

- Two independent components can be put together into an **AND-state**, separated by a dotted line

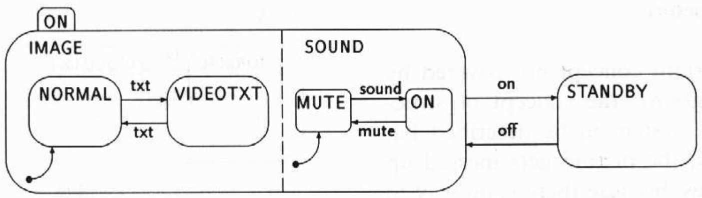


Fig. 4.

- Being in an AND-state means being in all of its immediate sub-states **at the same time**. This prevents the exponential blow-up familiar from composing FSMs in parallel.

Third concept: Broadcast

In our case we split state **normal** in two orthogonal components **channel**, for selecting channels, and **sm** for switching to mute:

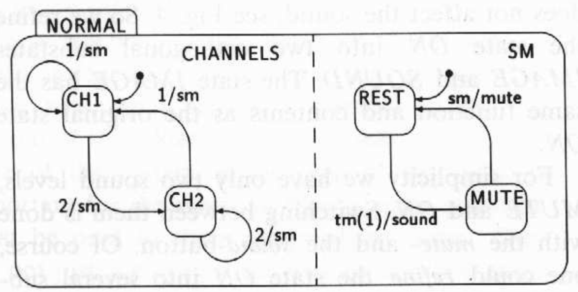


Fig. 5.

Behavior

- When a channel button (1 or 2, for simplicity) is pressed, one switches to that channel and the internal event **sm** is generated. This causes the event **mute** by a transition in **sm** to state **mute**, and the sound will be turned off.
- After **one second** the event **sound** is generated to turn the sound on, again. This is done by the special **time-out** event **tm(1)**.

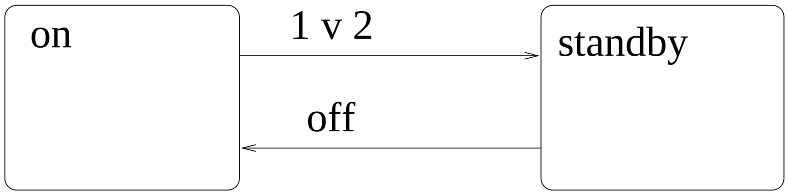
Actions and Transitions

Thus one sees that orthogonal components can communicate by generating events which are broadcast, and that this can be done in a time-dependent manner: introducing the **generation of events** $e/a_1; \ldots ; a_n$ and **time-out events tm(1), ...**

In general the label of a transition consists of two parts: a **trigger** that determines if and when a transition will be taken, and an **action** that is performed when a transition is taken. This action is the generation of a **set of events**.

Fourth concept: Compound events

When in state **standby**, dependent on whether one presses button 1 or 2 one makes sure to switch to states **ch1** or **ch2** in **on**. This is indicated as follows:



Transition Labels

- In general one can label transitions by **compound events** s.a. $(\neg a \wedge b) \vee c, a \wedge b, c \vee d, \neg a$, etc

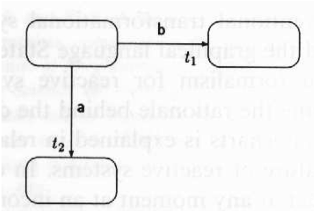


Fig. 7.

- E.g., in: a can be replaced by $a \wedge \neg b$ to express priority of event b over event a.

Summa Summarum

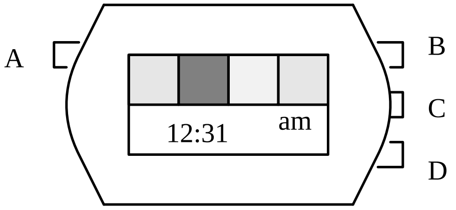
In a nutshell, one may say with David Harel:

$$
\begin{aligned}
\text{Statecharts} &= \text{Mealy Machines} \\
&+ \text{depth} \\
&+ \text{orthogonality} \\
&+ \text{broadcast} \\
&+ \text{data}
\end{aligned}
$$

Another Example

Alarm watch

As an example of a statechart we use that of a simple digital watch with four buttons A, B, C and D like in the below picture:



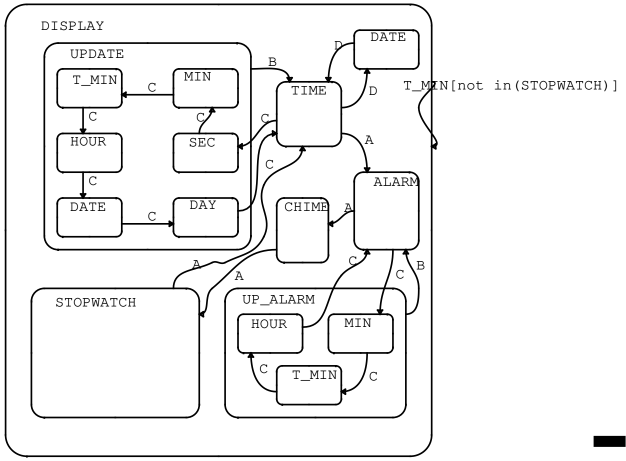
Events

The following events are considered as external:

- A, B, C and D describe the pushing of the four buttons and B_up the release of button B.
- The events Bt_In, Bt_Rm, Bt_Dy and Bt_Wk describe respectively the putting in, removal, drop dead and weakening of the battery.
- T_hits_Hr describes that the internal time has reached a whole hour and T_Hits_Tm describes that the internal time has reached the alarm time.
- T_Min describes that there are two minutes passed since for the last time a button has been pushed.

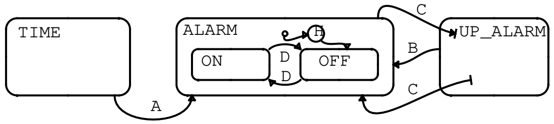
Display control

There is a special state $up - alarm$ for the changing of the internal state of the alarm. Note that T_min takes care of the resetting of a state.



History of states

A frequently used way to enter a group of states is by the history of that group. The most simple example of this is the one where you enter the most recently visited state of a group. In the watch example this happens in the zoom-in of the $alarm$ state with two substates on and off. The problem is that the initial default is the off state but when we put on the alarm we want to get back the next time in state on. In the next statechart this described by the **H** connector.



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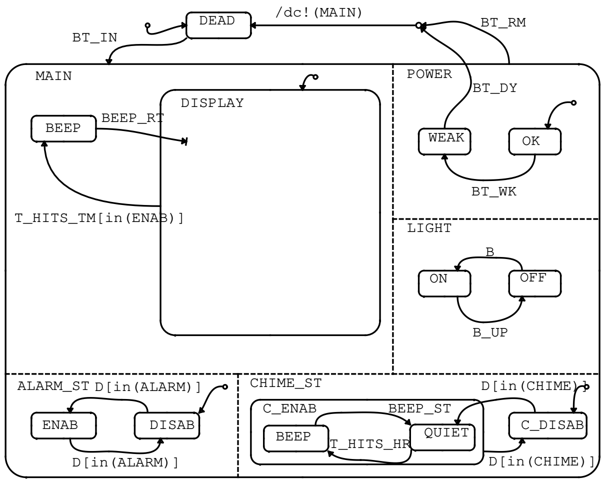
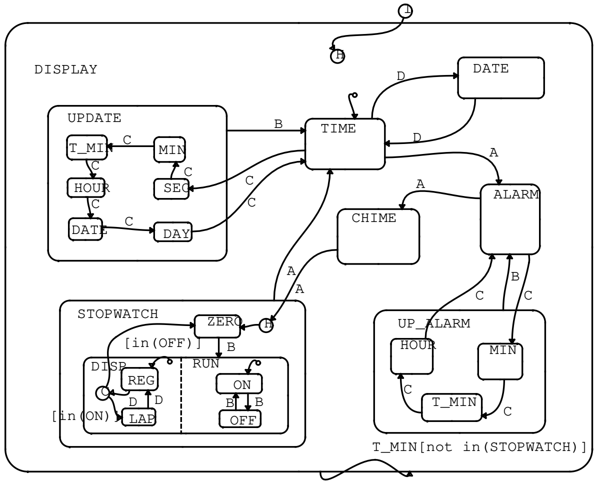


Display with Stopwatch



Events

The basic events and condition are external, for example for the watch the pressing of a button is an external event and T_Hits_Tm is an external condition. Besides the external events the following internal events are allowed:

$entered(S)$,	abbreviation	$en(S)$,
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Semantics of Statecharts — Lesson II

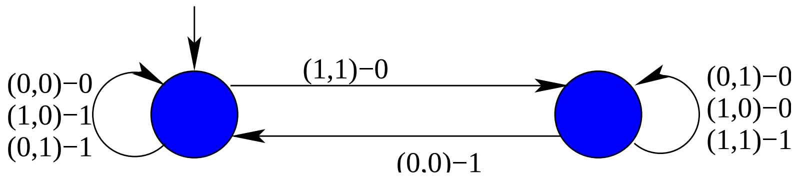
We discuss the central concepts and decisions for various possible semantics for Statecharts (and the “real” implemented one).

[HdR91] Introduction to Design Choices in the Semantics of Statecharts, C. Huizing, W.-P. de Roever, Information Processing Letters 37, p. 205-213, 1991

[HP98] Modeling Reactive Systems with Statecharts: The STATEMATE Approach, D. Harel, M, Politi. McGraw-Hill, 1998.

First Session

Serial Addition: Mealy Machine



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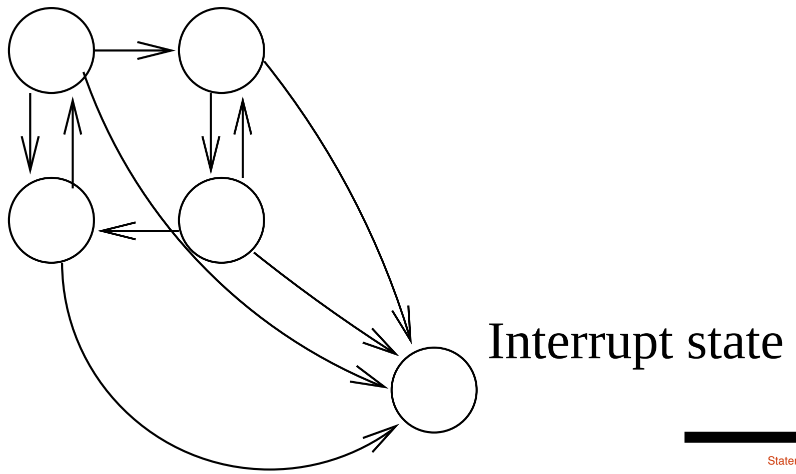

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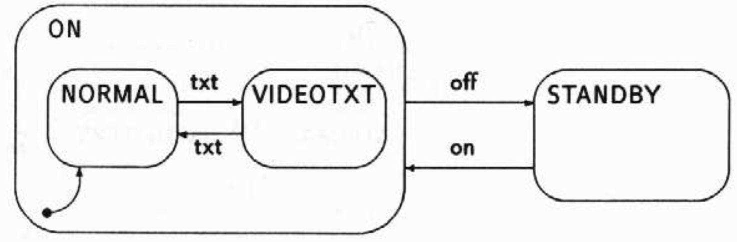

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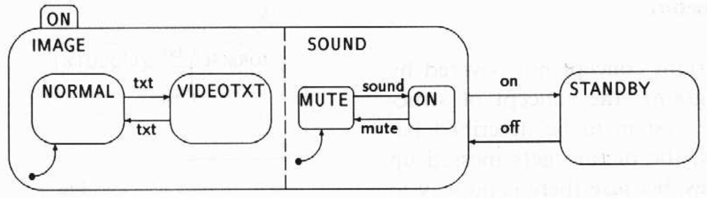

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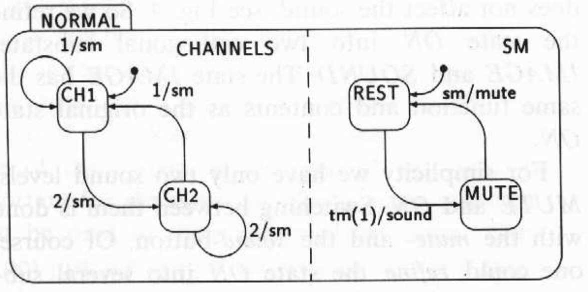

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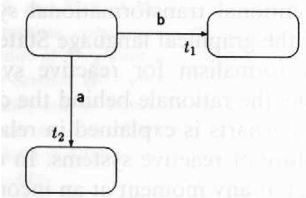

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Statecharts

Statecharts	$=$	Mealy Machines
	$+$	depth
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	$+$	broadcast
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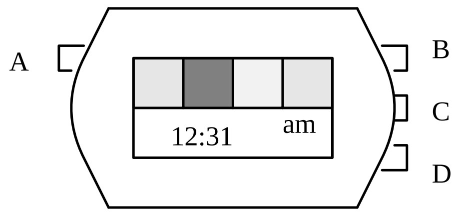

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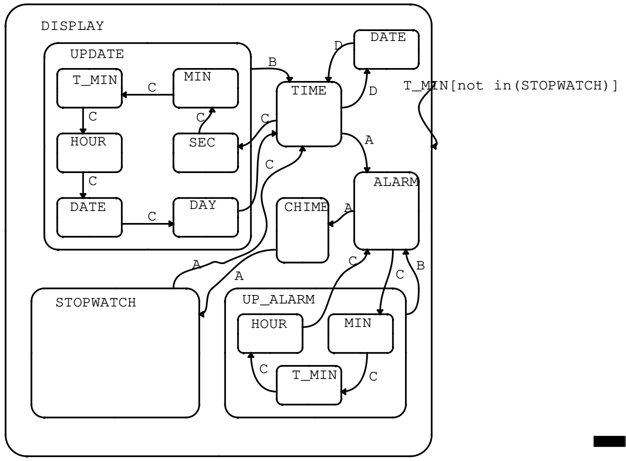

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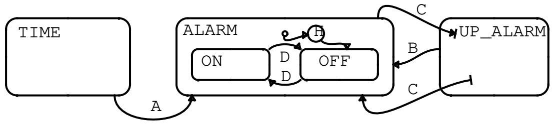

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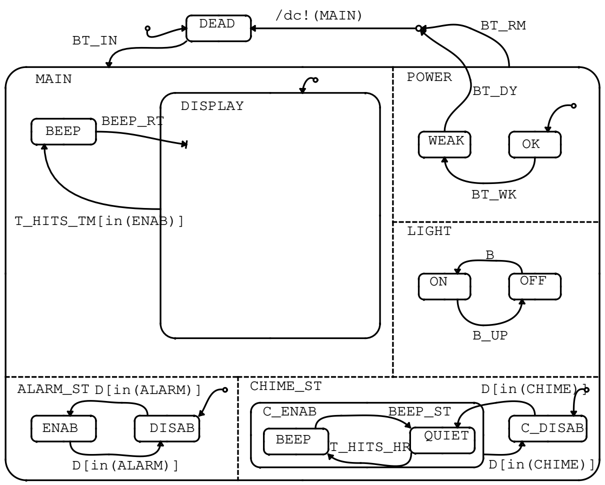

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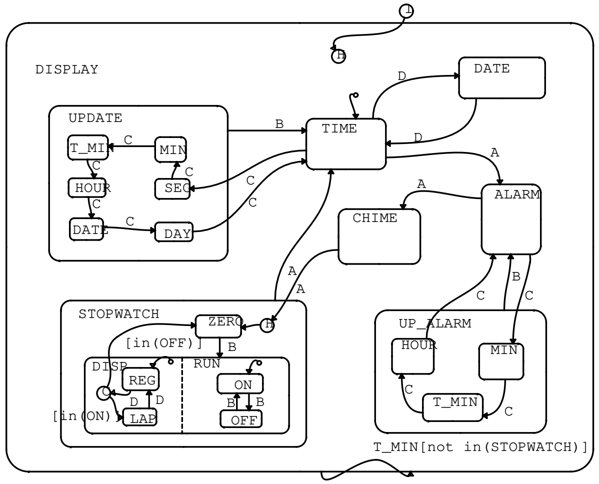

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Real-Time Systems

Real-Time Systems

- the environment can deliver data continuously, for example via temperature sensor.
- data can be delivered from different sources simultaneously and must therefore be processed in parallel.
- the time scale is fast by human standard (milli seconds instead of seconds),
- the system must react in time and accurately on input from the environment.

Characteristics

- the environment of a real-time systems contains often equipment that act as sensors of the systems (a typical example are optical scanners, that collect a continuous stream of relative unstructured data) and also equipment that can change the environment physical (like ‘actuators’ that continuously change the position of a tap).
- real-time systems must often simultaneously process input from different sources (in an industrial process control system, for example, the values of temperature, pressure and liquid concentration must be correlated simultaneously to execute adjustments of heating-apparatus and taps)

Characteristics

- the time scale of much real-time systems is fast considered to human standards (in an automated systems for the control of the speed of a car, for instance, the real speed must be measured many times a second to insure a comfortable ride; although this is fast for human standards, it is slow for real-time standards where the speed of operation is near the speed of the available implementation technology)
- real-time systems must react punctual and accurate on the input from the environment (a valid value on the wrong moment is often more worse that no value at all)
- the data in a real-time system has often a limited period of validity (think of for instance a green traffic light for an automated car control system)

Characteristics

- the observation of the environment by the real-time system is always behind so that there is an inconsistency between the perception and the real state of that environment
- a real-time system must be prepared for every possible situation that can happen in the environment and must be safe with respect to appearance of critical fault situations
- a real-time system must satisfy high reliability requirements: a guaranteed MTBF (Mean Time Between Failure) and MTTR (Mean Time To Repair), for instance, telephone exchanges are considered not to be out of order for more than 2 hours in 40 years.

Time in Statecharts

Time

- The elementary unit of observation in a reactive system is the **event**
- The **environment** sends events to the system to **trigger computations**, the system reacts to the environment by sending, or **generating**, events.
- Events are also means of **communication** between parts of a system.

Time (cont'd)

- Because one wants to specify reactive systems at the **highest level of abstraction** in a discrete fashion, events are **discrete signals**, occurring at a **point in time.**
- Events have **no duration**; they are generated from one state to another. Hence, transitions have a discrete uninterruptable nature and **all time is spent in states.**

Reason

In a reason system new inputs may arrive at any moment. Therefore the current state it is in should be always clear. Since transitions have no duration, there are no "transient" periods in between states.
Therefore, the reaction on a possible input is always well defined.

> Of course this is an abstraction from reality. (At deep levels of electronic implementations, one encounters levels where discrete reasoning makes no sense anymore)

Statecharts is meant to be a high level specification language, where this abstraction can be maintained and is appropriate.

Reaction Time

- We know that transitions have no duration, but **when** do they take place, relative to the trigger? And:

  HOW LONG DOES IT TAKE THE SYSTEM TO COMPUTE A REACTION UPON AN EXTERNAL EVENT?

- For transformational systems this is easy — the only important distinction is between finite and infinite values (corresponding to a final state or no final state)
- For reactive systems this is not enough:
  We have to know when an output occurs relative to the events in the input sequence (see Brock-Ackermann paradox) $\Longrightarrow$
  One has to determine **the reaction time of a sequence.**

What's the reaction time of a reactive systems upon an external event in the high level Specification Language Statecharts?

Possibility 1

Specify a concrete amount of time for each situation. This forces us to quantify time right from the beginning. **Clumsy**, and not appropriate at this stage of specification where one is only interested in the relative order and coincidence of events.

Possibility 2

Fix reaction time between trigger **a** and corresponding action **a** within **e/a** (the label of a transition) upon 1 time unit.
Doesn't work: Upon refining **question/answer** to a **question/consult** and a **consult/answer** transition, there's a change of time, which may have far reaching effects (because of **tm(n)**-events, e.g.)
$\Longrightarrow$

A fixed execution time for syntactic entities (transitions, statements, etc.) is not **flexible** enough.

Possibility 3

Leave things open: say only that execution of a reaction takes some positive amount of time, and see at a later stage (closer to the actual implementation) how much time things take.

Clumsy, introduces far too much nondeterminism.

Solution

Summary : We want the execution time associated to reactions to have following properties:

- It should be accurate, but not depending on the actual implementation.
- It should be as short as possible, to avoid artificial delays.
- It should be abstract in the sense that the timing behavior must be orthogonal to the functional behavior.

$\Longrightarrow$

Only choice that meets all wishes is **zero reaction time.**

Problems Disappear

As a result all objections raised w.r.t. the possibilities mentioned on the previous page are met!

- Now, for instance, upon refining transition **question/answer** from previous page into two transitions, the reaction time of this refinement is the same as that of the original transition.
- Objection 3 on the previous transparency is resolved, too.
- Finally, also objection 1 (on previous transparency) is met, because $0 + 0 = 0$!

Berry's synchrony hypothesis

This choice, that the reaction time between a trigger and its event is zero, is called **Berry's synchrony hypothesis.**
Is this implementable? No, a real computation takes time.
But in actual implementation this means:

The reaction comes before the next input arrives,

or, so to say,

Reactions are not infinitely fast but fast enough.

Example

See the following figure:

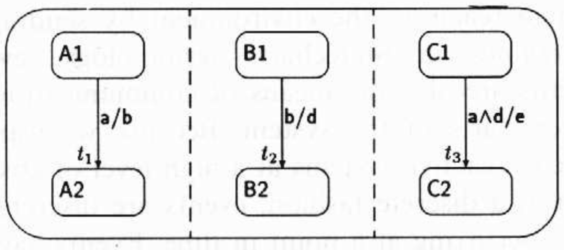


Fig. 6.

A consequence is that transition t_3 is taken!!

Negations and paradoxes

- Idea of immediate reaction works fine as long as transitions only triggered by primitive events, or or conjunctions and disjunctions of them.
- However, one also needs **negations of events** to trigger a transition. E.g.: to specify priority:

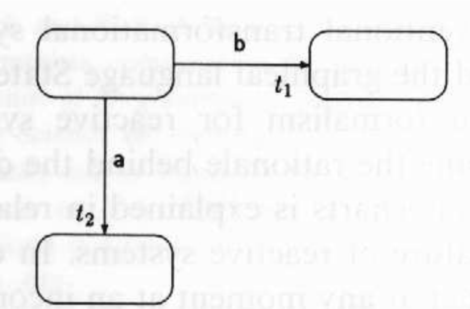


Fig. 7.

Problem

What semantics to give to Statecharts in the next figure?

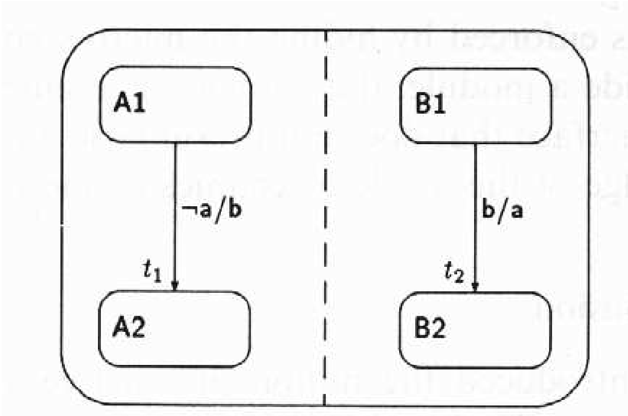


Fig. 8.

Grandfather Paradoxon

If **a** is absent, i.e., ¬**a** holds as condition, transition t_1 is taken, i.e., **b** is generated, and hence t_2, i.e., **b**/**a** is taken, generating **a within the same time unit**, i.e., in zero time, hence transition t_1 should not be taken.
But that means that event **b** is not generated, and hence event **a** is not generated, so transition t_1 should be taken, etc.
This is called the “Grandfather paradox”.
It’s solution is to **order** event occurrences causally, with **later events not influencing earlier events**:$\neg a \leq b \leq a$

Note here: this causal order has nothing to do with the passage of time; it merely refers to causal chains **within** one time step.

Solution

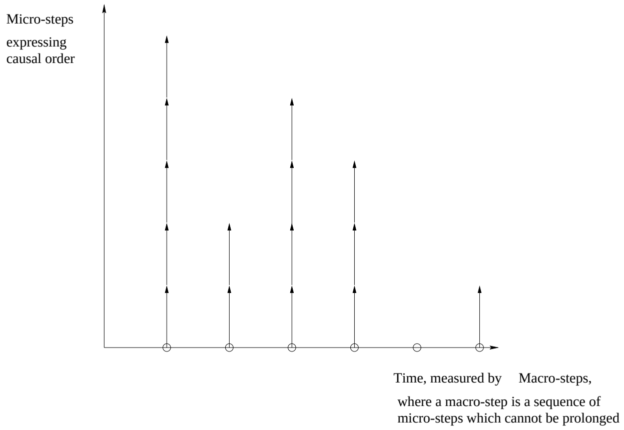
Introduce two levels of time

- **Macro steps**, for counting time, (these are observable) time steps, and
- **Micro steps**, which describe the causal chain within reactions.
  Every macro-step is then divided in an arbitrary but finite number of micro-steps.

This sequence of micro-steps has only an operational meaning.

The New Semantics

This leads to a semantics of the following form:



The New Semantics (cont'd)

- Macro-steps are observable steps $\Longrightarrow^{O}_{I}$
- Each macro-step is a sequence of micro-steps, that are ordered causally; one micro-step can never influence previous micro-steps.
- In Statecharts as implemented by Statemate causality is trivially obtained because in Statemate events generated in one step are only available in the next step, and only for that one. I.e., there is no causality within one step.

Problems with New Semantics

The problem with macro-steps is that they lead to a **globally inconsistent** semantics.

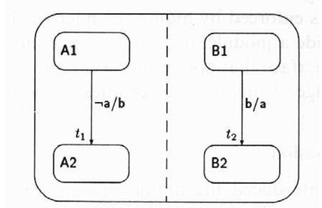


Fig. 8.

$$S_1 \Longrightarrow^{b}_{\emptyset} S_2 \Longrightarrow^{a}_{b} S_3$$

Here absence of triggers generates presence of triggers, which violates their absence within the same step.

Fundamental Question

Is a semantics for such languages possible which satisfies all “reasonable” assumptions? I.e., which is both good for program development and for program composition?

The answer is **NO**.

"Reasonable" Assumptions

Let's list a couple of desirable properties of such a semantics:

Responsiveness: Reactions are simultaneous with their triggers — this facilitates refinement of transitions from a high to a lower level.

Modularity: Modules can be composed on the basics of their macro-steps, i.e., the external interface of a (parallel) composition of modules is of the same nature as their mutual interface w.r.t. each other. (This is inspired by a paper by Pnueli and Shalev)

Causality

Without a causal order of the micro-steps inside a macro-step, charts s.a.:

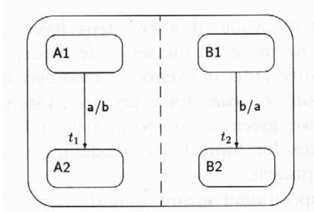


Fig. 9.

would trigger each other, which makes no causal sense. Such charts are excluded imposing causality.

Impossibility Result

Modularity, causality, and responsiveness can be mathematically expressed; the **impossibility** of all three being satisfied simultaneously becomes a theorem, proved in the paper by Huizing and Gerth.
However, also intuitively this is clear:

- Causality and responsiveness leads to examples in which both a and its absence $\neg a$ occur within the same macro-step $\Longrightarrow$ no global consistency $\Longrightarrow$ no modularity
- Modularity and responsiveness imply there exists no satisfactory semantics for the example above. This choice is made in the synchronous language ESTEREL, in which examples as the one above are excluded on syntactic grounds by a compiler.

Compositional Semantics

This is a serious problem. As it turns out, the semantics with macro-steps indicating passage of time, and refined by causally ordered micro-steps is a basis for a compositional semantics for Statecharts in which the semantics of a construct is a function of the semantics of its parts. But this semantics turns out to be too difficult to handle for the engineers of I-Logix, and of Israeli Aircraft Industries, its main customer for the Statemate system.

> Hence looking for a "best" semantics makes a lot of sense. What our theorem below says is that, in a certain sense, there is no best semantics. However, it does leave some room for the search for ever better semantics!!

Classification of possible semantics for Statecharts

Several Classes of Semantics

Next we list a few possible semantics for Statecharts, semantics A – E, of which E is closest to the one actually implemented in Statemate, and discuss the anomalies allowed by them (including those of the implemented semantics of Statecharts).

Semantics A

Events generated as a reaction to some input can only be sensed in the step following that input.
Anomaly: no simultaneity of action and reaction, i.e., no responsiveness. In semantics A the trigger $a \wedge d$ will not occur:

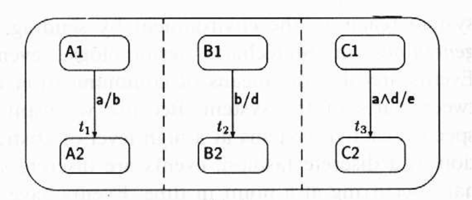


Fig. 6.

This example makes clear that in semantics A the moment of generation of an event is too important — a too detailed analysis of charts is required for adopting it.

Semantics B

In order to overcome the problem with semantics A, absence of responsiveness, micro-steps are introduced, with events sensed in the next micro-step.
Then, in the previous example the third transition is taken.
Consider now the trigger $b \wedge \neg d$ for the third transition; the transition is taken, because in the second micro-step, event c is not yet sensed. This example also works for semantics A.
Disadvantage: Semantics B is too subtle to be of any practical use; same objection as to semantics A.

Semantics C

Requires global consistency of **every** micro-step. The reaction of the system to an input should

- not only be enabled by events generated in previous micro-steps
- but also by events generated in the full macro-step.

As a consequence, the $b \wedge \neg d$ transition is not taken.

Semantics C (cont'd)

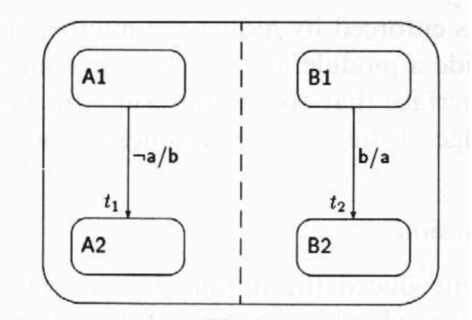


Fig. 8.

This example is excluded in semantics C, leads to contradiction. I.e., syntactical means must be found to exclude it, as done in ESTEREL by a compiler.

Semantics C (cont'd)

This makes a lot of sense, as evidenced by the considerable success of ESTEREL of Gérard Berry.

However, this semantics is not modular. This implies that a modular development of the system is cumbersome, since every developer has to know the detailed micro-behavior of the other processes. Hence, this semantics is appropriate for top-level guys only, and that's what Gérard Berry's crowd consists of.

Semantics D

All events generated during some macro-step considered as if they were present right from the beginning of the macro-step. Semantics D allows

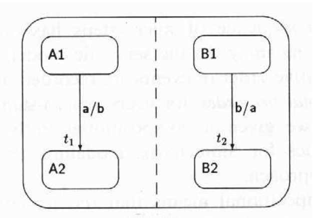


Fig. 9.

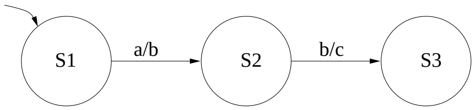
to be taken: reactions may trigger themselves. I.e., semantics D is not causal.
Note: In semantics D, the external world does not generate an a event!
Conclusion: This example should be rejected!

Semantics E

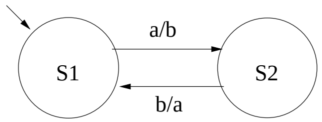
Events are generated at the next step, but no input from the environment is possible **before** the reaction of the system has completely died out.

> This semantics is heavily non-modular, since one macro-step may contain several steps of the A semantics. Events remain active only for the duration of such a step, hence, in one macro-step an event can be activated and deactivated several times, thus leading to a much more complex interface between subsystems, than between the system and its environment.

Semantics E (cont'd)



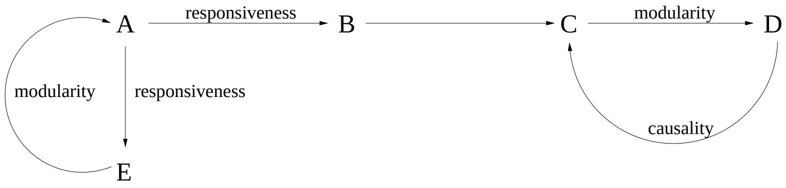
Generation of event a leads the system eventually to state S_3.



In semantics E, as in the implemented semantics of Statecharts, this example leads to an infinite loop (the so-called: "go repeat" mode): try it out yourself!

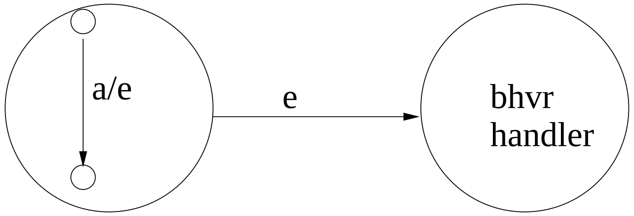
Situation

No "best" semantics $\Longrightarrow$ still room for better ones
The situation is summarized in the following figure, showing how each semantics is an attempt to improve on the other one:



Search for better Semantics

Several cleaner semantics have been proposed, notably by Florence Maraninchi. She opts for semantics D, in which both charts such as example C and D are excluded, resulting in Argos semantics:



Generation of event a leads to exit transition e being taken.

This is called **non-preemptive interrupts**.

Argos Semantics

The Argos semantics leads to a cleaner concept of state-hierarchy in which **inter-level transitions are not allowed.** Probably a too heavy investment in their “old” semantics, manyear-wise, prevented I-Logix from adopting the cleaner Argos semantics of Maraninchi in Statemate.

> Huizing and Gerth propose a compositional semantics in which the causal chains inside a module are hidden from its external behavior. This proposal has not yet caught on.

Statecharts as Implemented

This leaves us with the semantics of Statecharts as it is implemented in Statemate. Computing that semantics is a fairly involved algorithm, only recently (1996) published in a paper by David Harel and A. Naamad.

Operational semantics

We describe the contents of the system status, and the algorithm for executing a step.

Statecharts Status

- a list of states in which the system currently resides;
- a list of activities that are currently active;
- current values of conditions and data-items;
- a list of regular and derived events that were generated internally in the previous step;
- a list of timeout events and their time for occurrence;
- a list of scheduled actions and their time for execution;
- relevant information on the history of states.

Input

The **input** to the algorithm consists of:

- the current system status;
- a set of external changes that occurred since the last step;
- the current time

The **step** execution algorithm works in three main phases.

Step Algorithm: First Step

- calculate the events derived from the external changes and add them to the list of events;
- perform the scheduled actions whose scheduled time has been exceeded, and calculate their derived events;
- update the occurrence time of timeout events if their triggering events have occurred;
- generate the timeout events whose occurrence time has been exceeded;

Step Algorithm: Second Step

- evaluate the triggers of all relevant transition reactions;
- prepare a list of all states that will be exited and entered;
- evaluate the triggers of all static reactions

Step Algorithm: Third Step

- update the history of states;
- carry out all computations prescribed by the actions in the list produced in the second phase;
- carry out all updates called for by the actions
- update the list of current states.

Synchronous/Asynchronous Semantics

Synchronous Semantics: Environment interacts with the system after each step and time advances. This is conceptually quiet easy and appropriate for synchronous hardware. But, the system's reaction on the external input has to be simple (compare with semantics A).

Asynchronous Semantics: Synchrony Hypothesis: system may react with a chain reaction. External input only in **stable** states. Easier to model complex systems, abstraction from real-time. But, the implementation has to be shown to satisfy the assumptions of zero reaction time.

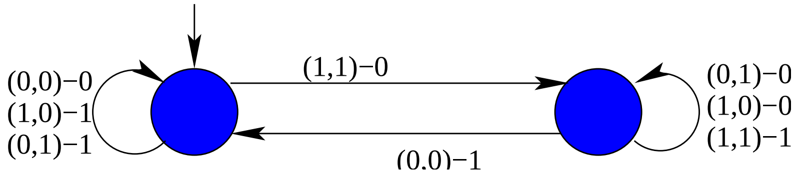
The STATEMATE *Toolset — Lesson III*

The notion of a reactive system and the language Statecharts were introduced in the last session. We explained the rationale behind the design decisions of Statecharts in relation to the specific nature of reactive systems.
This time, the role of models in a system development life cycle is described. We introduce three languages to characterize reactive systems from different views. This results in a brief description of the STATEMATE toolset

[HP98] Modeling Reactive Systems with Statecharts: The STATEMATE Approach, D. Harel, M, Politi. McGraw-Hill, 1998.

Last Session

Serial Addition: Mealy Machine



Statecharts

Statecharts	$=$	Mealy Machines
	$+$	depth
	$+$	orthogonality
	$+$	broadcast
	$+$	data

Time

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- For transformational systems this is easy — the only important distinction is between finite and infinite values (corresponding to a final state or no final state)
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Reaction Time

Summary : We want the execution time associated to reactions to have following properties:

- It should be accurate, but not depending on the actual implementation.
- It should be as short as possible, to avoid artificial delays.
- It should be abstract in the sense that the timing behavior must be orthogonal to the functional behavior.

$\Longrightarrow$

Only choice that meets all wishes is **zero reaction time.**

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Solution

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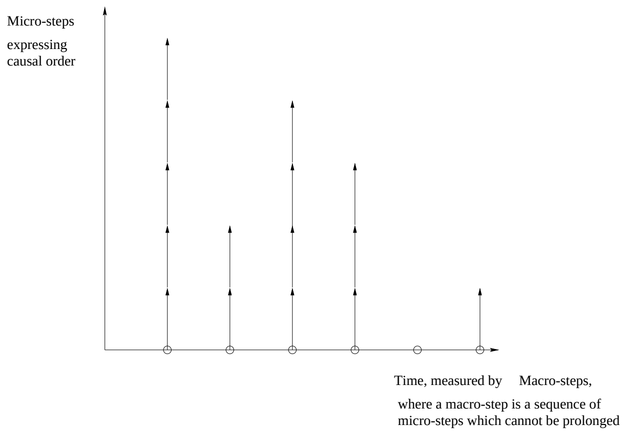
The New Semantics

This leads to a semantics of the following form:



Problems with New Semantics

The problem with macro-steps is that they lead to a **globally inconsistent** semantics.

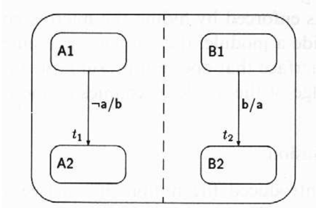


Fig. 8.

$$S_1 \Longrightarrow^{b}_{\emptyset} S_2 \Longrightarrow^{a}_{b} S_3$$

Here absence of triggers generates presence of triggers, which violates their absence within the same step.

Systems Life Cycle

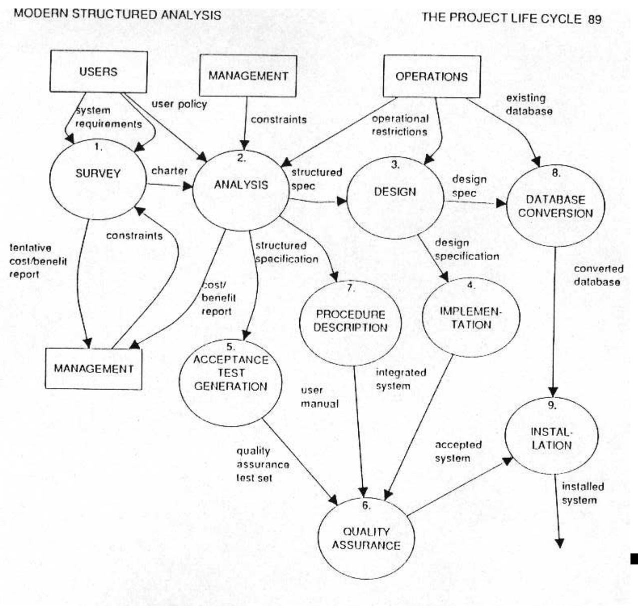
Specification in a systems life cycle

- Identify several phases in the development life cycle of a system
- **Classic waterfall model**: requirements analysis, specification, design, implementation, testing, and maintenance.
- Other approaches center around prototyping, incremental development, reusable software, or automated synthesis.

Requirements Analysis

- Most proposals contain a requirements analysis phase. Specification errors and misconceptions should be discovered in that early phase.
- Correcting errors in later stages is extremely expensive.
- Special languages are therefore used in the requirements analysis phase to specify a model of the system, and special techniques are used to analyze it extensively.

System's life cycle



System Model

- A good model is important for all participants in the system's development.
- Having a clear and executable model the functionality and behavior can be approved before investigating heavily in the implementation stages.
- The specification team uses modeling as the main medium for expressing ideas.

Methodology

A methodology provides guidelines for performing the processes that comprise the various phases.
Concentrating on the modeling and analysis phase, a methodology consists of the following components:

- The methodology's underlying approach and the concepts it uses.
- The notation used, that is, the modeling languages with their syntax and semantics.
- The process prescribed by the methodology, that is, which activities have to be carried out to apply the methodology and in what order.
- The computerized tools that can be used to help in the process.

Reactive systems

The Statecharts language is especially effective for reactive systems.
A typical reactive system exhibits the following distinctive characteristics:

- It continuously interacts with its environment, using inputs and outputs that are either continuous in time or discrete.
- It must be able to respond to interrupts, i.e., high-priority events.
- Its operation and reaction often reflect stringent time requirements.
- It is very often based on interacting processes that operate in parallel.

Examples

On-line interactive systems: e.g., automatic teller machines, flight reservation systems

Computer-embedded systems: avionics, automotive, and telecommunication systems

Control systems: such as chemical and manufacturing systems.

The early warning system

A system model constitutes a tangible representation of the system's conceptual and physical properties and serves as a vehicle for the specifier and designer to capture their thoughts.

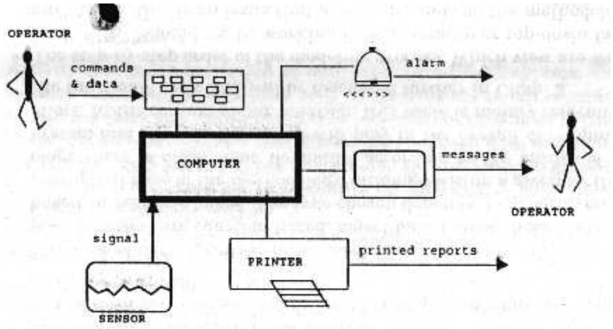


Figure 1.1 The early warning system (EWS).

Characteristics of models

Beside for communication, systems models should also be used for inspection and analysis.

When the model reflects some preexisting descriptions, such as requirements written in natural language, it is useful to keep track of how the components of the developing model are derived from the earlier descriptions.

STATEMATE

The modeling languages used in STATEMATE have been designed with several important properties in mind:

- to be intuitive and clear
- to be precise
- to be comprehensive
- to be fully executable

How to achieve these properties?

- To achieve clarity, elements of the model are represented graphically wher ever possible.
- For precision, all languages features have rigorous mathematical semantics
- Comprehension comes from the fact that the languages have the full expressive power needed to model all relevant issues, including the what, the when, and the how.
- For executability, the behavioral semantics is detailed and rigorous enough to enable the model to be executed (or be used to generate code).

Modeling Views

Building a model can be considered as a transition from ideas and informal descriptions to concrete descriptions that use concepts and predefined terminology.

Here, the descriptions used to capture the system specification are organized into three views: the **functional**, the **behavioral**, and the **structural**

Illustration

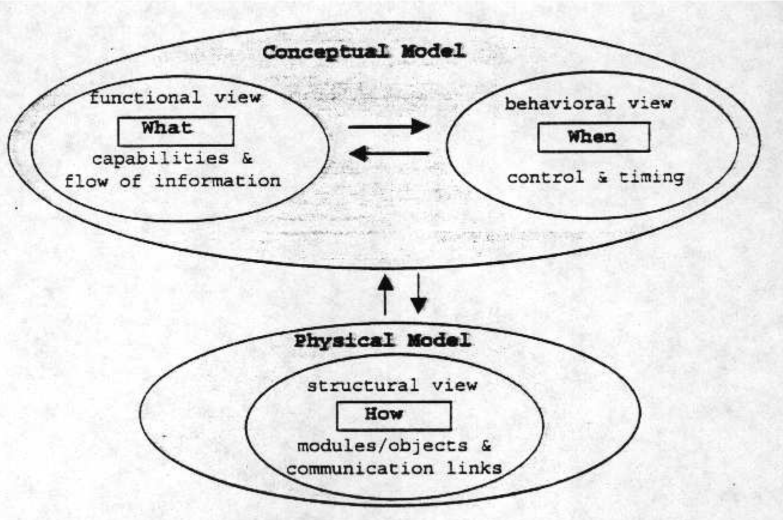


Figure 1.2 The three specification views.

The Three Views

Functional view : The functional view captures the “what”. It describes the system’s functions, processes, or objects, also called activities, thus pinning down its capabilities. This view includes the inputs and outputs of the activities.

Behavioral view : The behavioral view captures the “when”. It describes the system’s behavior over time, including the dynamics of activities, their control and timing behavior, the states and modes of the system, and the conditions and events that cause modes to change and other occurrences to take place.

Structural view : The structural view captures the “how”. It describes the subsystems, modules, or objects constituting the real system and the communication between them.

Connection

While the two former views provide the conceptual model of the system, the structural view is considered to be its physical model.
The main connection between the conceptual and physical models is captured by specifying the modules of the structural view that are responsible for implementing the activities in the functional view.

Modeling Heuristics

Modeling heuristics are guidelines for how the notation should be used to model the system.

- The mapping between the methodology's concepts and the elements allowed in the notation.
- The type of decomposition to be used: e.g., function based, object based, mode based, module based, or scenario based.
- The step-by-step order of the modeling process: bottom-up or top-down

The Modeling Languages

The three views of a system model are described in our approach using three graphical languages.

- **Activity-charts** for the functional view,
- **Statecharts** for the behavioral view,
- and **Module-charts** for the structural view.
- Additional non-graphical information related to the views themselves and their inter-connections is provided in a **Data Dictionary**

Illustration

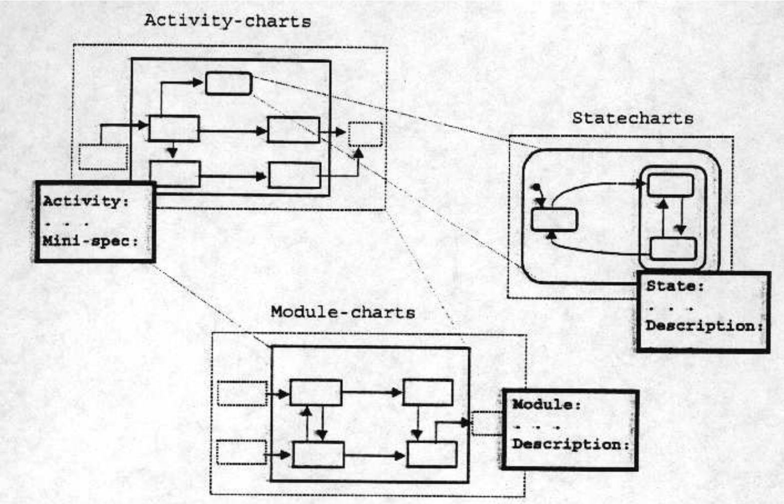


Figure 1.3 The modeling languages.

Activity-charts

Activity-charts can be viewed as multilevel data-flow diagrams. They capture functions, or activities, as well as data-stores, all organized into hierarchies and connected via the information that flows between them.

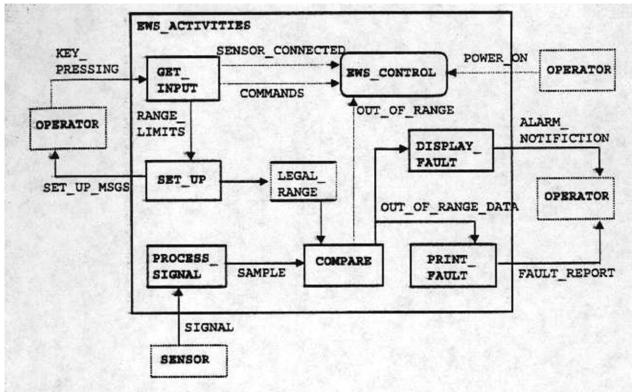
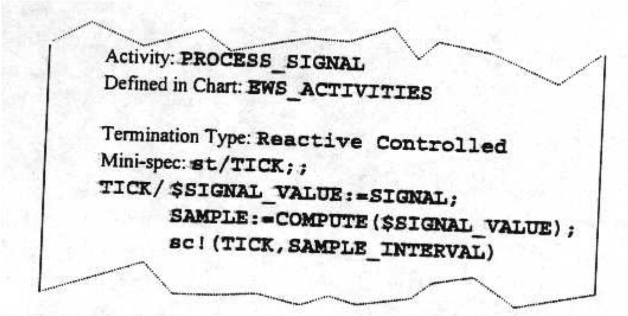


Figure 1.4 An activity-chart.

Non-graphical information

In addition to the graphical information, each element in the described has an entry in the Data Dictionary, which may contain non-graphical information about the element. For example, the activity entry contains fields called mini-spec and long description, in which it is possible to provide formal and informal textual descriptions of the activities workings.



Activity: PROCESS_SIGNAL
Defined in Chart: EWS_ACTIVITIES

Termination Type: Reactive Controlled
Mini-spec: st/TICK;;
TICK/ $SIGNAL_VALUE:=SIGNAL;
SAMPLE:=COMPUTE($SIGNAL_VALUE);
sc!(TICK,SAMPLE_INTERVAL)

Statecharts

Statecharts constitute an extensive generalization of state-transition diagrams. They allow for multilevel states decomposed in an and/or fashion, and thus support economical specification of concurrency and encapsulation. They incorporate a broadcast communication mechanism, timeout and delay operators for specifying synchronization and timing information, and a means for specifying transitions that depend on the history of the system's behavior.

EWS-Statecharts

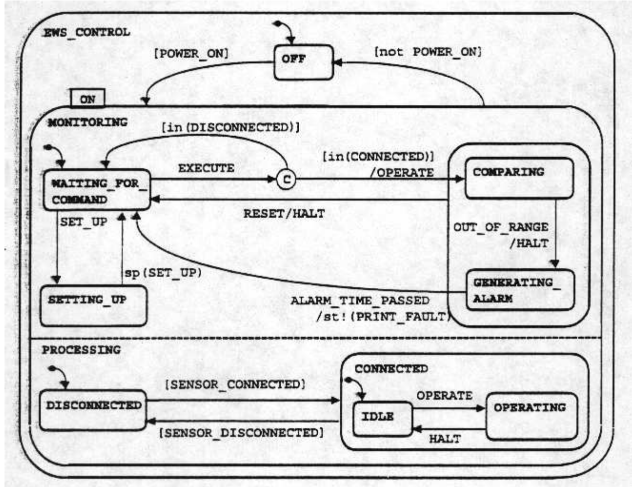
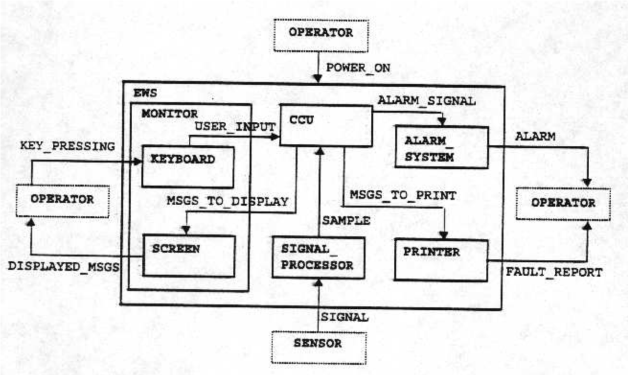


Figure 1.6 A statechart.

Module-charts

A module-chart can also be regarded as a certain kind of data-flow diagram or block diagram. Module-charts are used to describe the modules that constitute the implementation of the system, its division into hardware and software blocks and their inner components, and the communication between them.



Relationship between the languages

The relationship between the concepts of the three views are reflected in corresponding connections between the three modeling languages.
Most of these connections are provided in the Data Dictionary, and they tie the pieces together, thus yielding a complete model of the system under development.

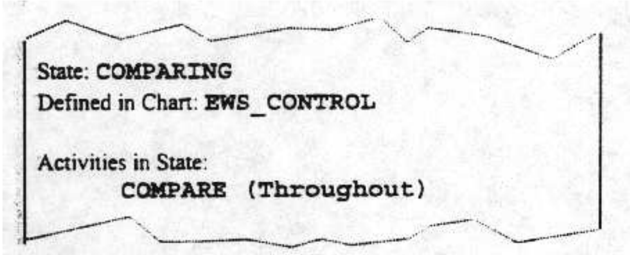


Figure 1.8 Specifying an activity throughout a state.

Handling large-scale systems

- The languages allow to split large hierarchical charts into separate ones:

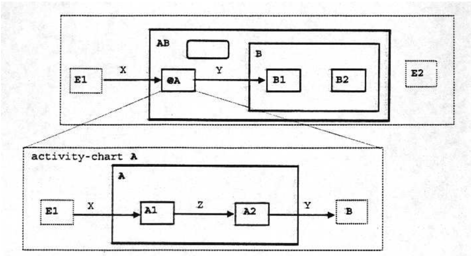


Figure 1.10 Splitting up charts.

- Also, coping with visibility and information hiding by setting scoping rules of elements in the model.
- Moreover, **generic charts** and **user-defined types**.

The STATEMATE toolset

STATEMATE has been constructed to "understand" the model and its dynamics. The user can then execute the specification by emulating the environment of the system under development and letting the model make dynamic progress in response.

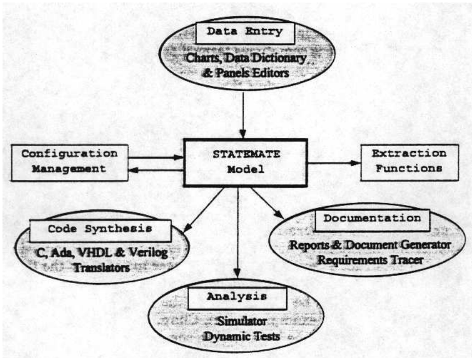


Figure 1.11 The STATEMATE toolset.

Activity-Charts

Describing the functional view of a system

Activity-charts are used to depict the functional view of a system under development (SUD), “what the SUD does”.

System’s Specification

- a hierarchy of functional components, called **activities**,
- what kind of information is exchanged between these activities and is manipulated by them,
- how this information flows,
- how information is stored, and
- how activities are **started and terminated**, i.e., **controlled**, if necessary, and whether activities are **continuous**, or whether they **stop by themselves**.

Hierarchical Data Flow Diagrams

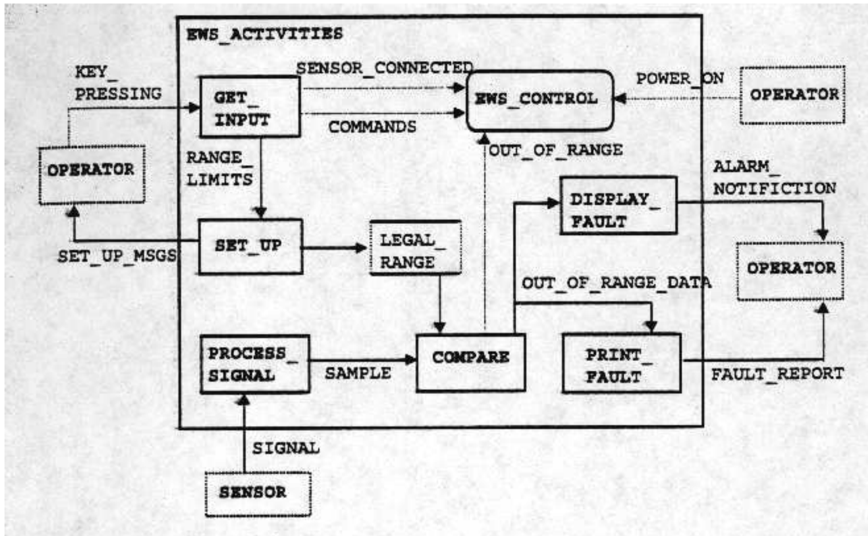


Figure 1.4 An activity-chart.

Functional decomposition of a System

The functional view of a system specifies the system's **capabilities.**
It does so in the context of the system's environment, that is, it defines the environment with which the system interacts and the interface between the two:

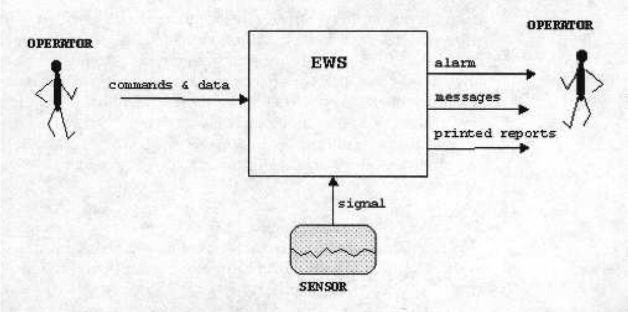


Figure 2.1. The context of the EWS

Structural View

This functional view does not address the physical and implementation aspects of the system; the latter is done in its **structural** view, i.e., its **module-chart**:

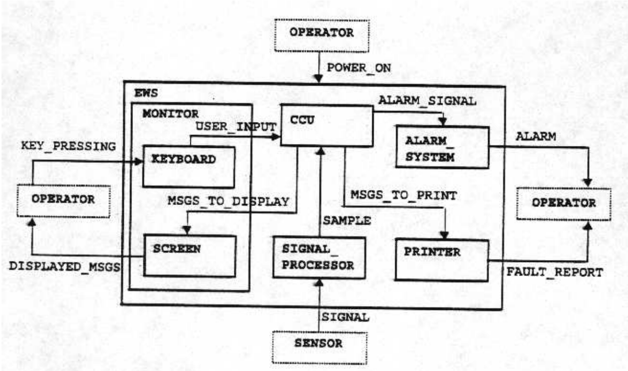


Figure 1.7 A module-chart.

Behavioral Aspects

Moreover it separates the dynamics and behavioral aspects of the SUD from its functional description. The former is done by its **behavioral** view, in its controlling Statecharts:

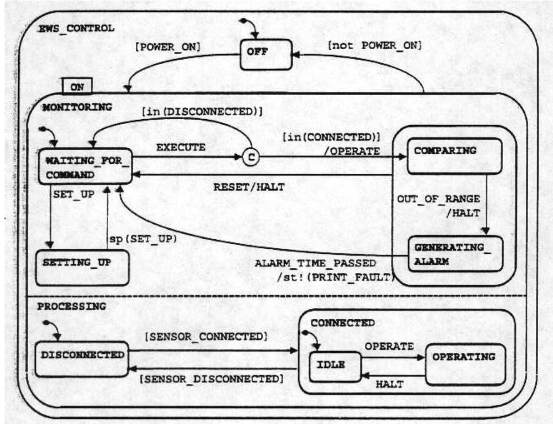


Figure 1.6 A statechart.

Example

The **functional view** tells whether a medical diagnosis system can monitor a patient's functions, and, if so, where it gets its input data and which functions have access to the output data.

The **behavioral view** tells under which conditions monitoring is started, whether it can be carried out parallel to temperature monitoring, and how the flow of control of the process of monitoring develops.

The **structural view** deals with the sensors, processors, monitors, software modules and hardware necessary to implement the monitoring system

The three views

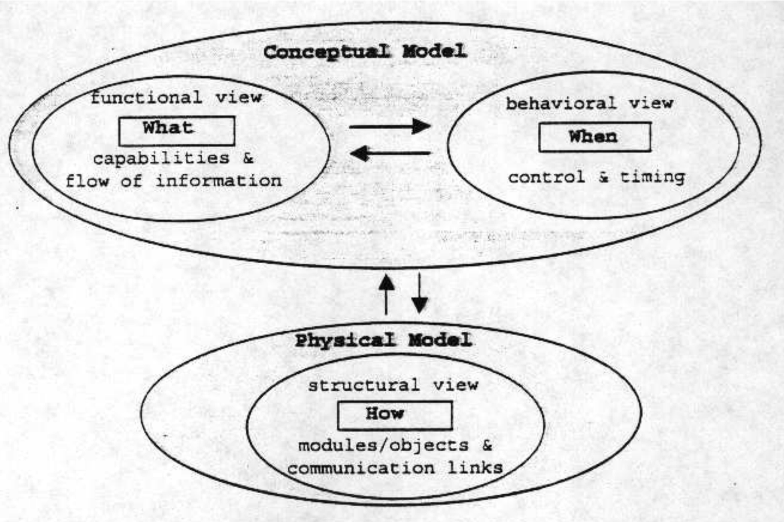


Figure 1.2 The three specification views.

Illustration

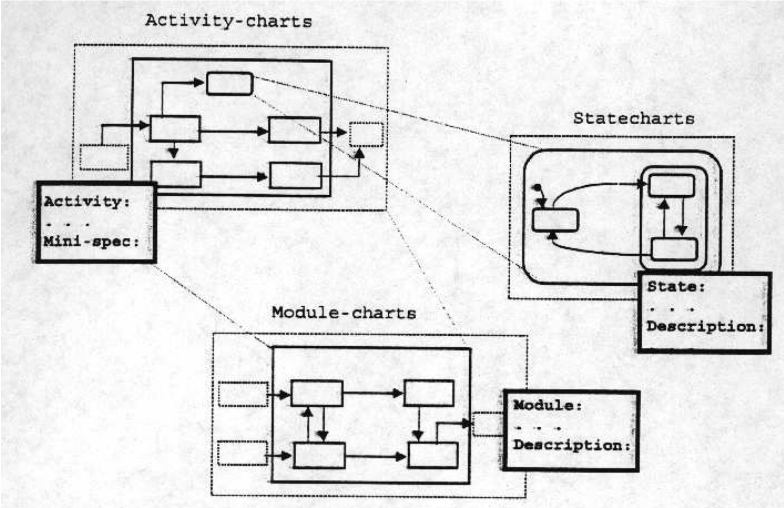


Figure 1.3 The modeling languages.

Functional Decomposition

In the Statechart approach, the functionality of a system is described by **functional decomposition**, by which a system is viewed as a collection of interconnected functional components, called **activities**, organized into a hierarchy.

EWS_ACTIVITIES

E.g., in the activity-chart EWS_ACTIVITIES, the SET_UP components can be decomposed leading to a multi-level decomposition of EWS_ACTIVITIES:

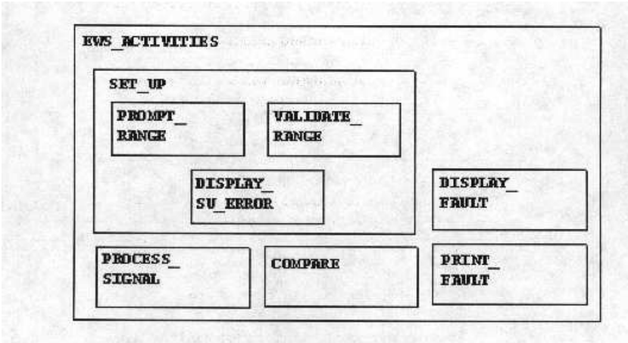


Figure 2.3. Multi-level decomposition of an activity

Functional Decomposition (cont'd)

- Each of the activities may be decomposed into subactivities repeatedly until the system is specified in terms of **basic activities**.
  There are specified using textual description (formal or informal), or code in a programming language, inside the Data Dictionary.
- The intended meaning of the functional decomposition is that **the capabilities of the parent activity are distributed between its subactivities.**

Functional Decomposition (cont'd)

- The **order** in which these subactivities are performed, and the **conditions** that cause their **activation** or **deactivation** are not represented in the functional view and are specified in the **behavioral view**, i.e., in the (one) statechart associated with the parent activity-chart.
- Activities can represent **objects, processes, functions, logical machines**, or any other kind of **functionally distinct entity**.
- In the following sections we'll confine ourselves to **function-based decomposition** of an activity-chart. We shall not discuss **object-based decomposition** (see Section 2.1.3 of Harel & Politi)

Function-based Decomposition

In function-based decomposition, the activities are (possibly reactive) functions.

The EWS receives a signal from an external sensor. When the sensor is connected, the EWS processes the signal and checks if the resulting value is within a specified range. If the value of the processed signal is out of range, the system issues a warning message on the operator display and posts an alarm. If the operator does not respond to this warning within a given time interval, the system prints a fault message on a printing facility and stops monitoring the signal. The range limits are set by the operator. The system becomes ready to start monitoring the signal only after the range limits are set. The limits can be re-defined after an out-of-range situation has been detected, or after the operator has deliberately stopped the monitoring.

Function-based Decomposition (cont'd)

Next we decompose this narrative to describe its functionality:

- The EWS receives a signal from an external sensor.
- It samples and processes the signal continuously, producing some result.
- It checks whether the value of the result is within a specified range that is set by the operator.
- If the value is out of range, the system issues a warning message on the operator display and posts an alarm.
- If the operator does not respond within a given time interval, the system prints a fault message on a printing facility and stops monitoring the signal.

Function-based Decomposition (cont'd)

Thirdly, we identify the various functions that are described by there requirements:

SET_UP: receives the range limits from the operator.

PROCESS_SIGNAL: reads the "raw" signal from the sensor and performs some processing to yield a value that is to be compared to the range limits.

COMPARE: compares the value of the processed signal with the range limits.

DISPLAY_FAULT: issues a warning message on the operator display and posts an alarm.

PRINT_FAULT: prints a fault message on the printing facility.

Function-based Decomposition (cont'd)

Notice that this description also contains info about handled data. An activity may **transform** its input into output to be consumed by other functions, which are **internal** or **external** to the system:

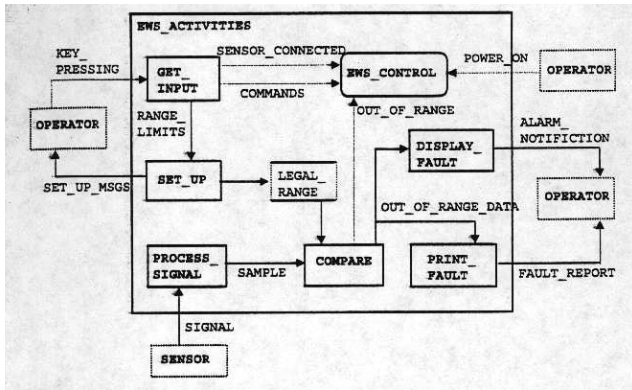


Figure 1.4 An activity-chart.

System Context

One of the first decisions to be made when developing a system involves its **boundaries**, or, **context**. I.e., one must determine which entities are part of the environment of a system, and how they communicate with the system. The latter are called **external activities** of the system.

EWS-Example

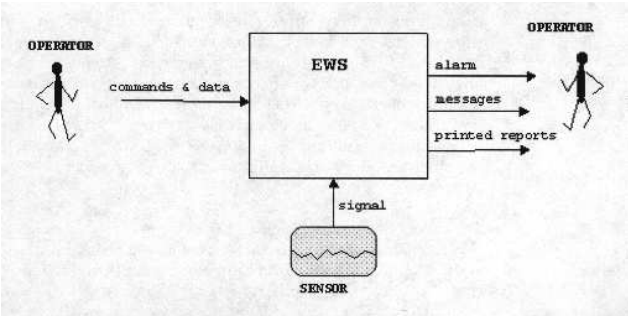


Figure 2.1. The context of the EWS

Notice that for the EWS one might have chosen for the printer to be external, leading to printer as external activity.

Different occurrences of the same entity (here: operator) denote the same entity; these are multiplicated of ease of drawing.

Decomposition process

The functional view is specified by **Activity-charts**, together with a **Data Dictionary** that contains additional information about the elements appearing in the charts, e.g., about their basic activities.

Activities and their representation

We continue the functional decomposition of the EWS, started with:

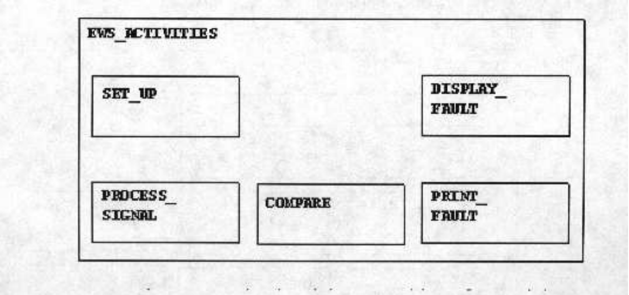


Figure 2.2. First level decomposition of an activity

This activity chart contains one top-level box, representing the **top-level activity** of the chart.

Top-Down Development

On their turn, the activities appearing above can be decomposed themselves, as SET_UP:

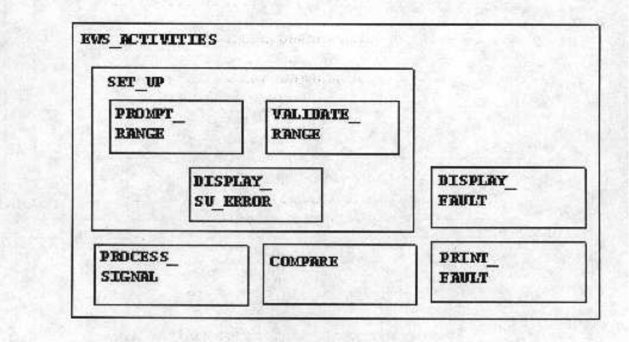


Figure 2.3. Multi-level decomposition of an activity

Some terminology

- EWS_ACTIVITIES is called **top-level activity**
- EWS_ACTIVITIES is also called **parent activity** of SET_UP, COMPARE, etc., which are called **descendants** of EWS_ACTIVITIES, as are the subactivities PROMPT_RANGE etc. of SET_UP, who have SET_UP and EWS_ACTIVITIES as **ancestor.**

Each activity has a corresponding item in the Data Dictionary, which may contain additional information.

Flow of Information between Activities

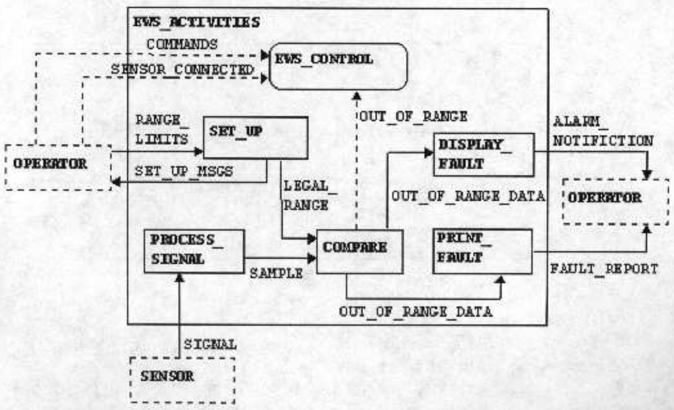


Figure 2.5. **EWS_ACTIVITIES**, its environment and flow of information

Information Flow in EWS

- OPERATOR and SENSOR are external activities, drawn using dotted lines.
- Different occurrences of OPERATOR refer to the same entity.
- Solid arrows denote **data-flow-lines** between activities.
- Control of EWS_ACTIVITIES is handled in its **control activity chart** EWS_CONTROL, a statechart (drawn using rounded corners).
- Dotted arrows denote **control-flow-lines**, carrying info or signals used in making **control decisions**.

Flow lines

A label on a flow line denotes either a single information element that flows along the line, i.e., a **data-item**, **condition**, or **event** or a group of such elements, as in, e.g.:

Data-Item: **SIGNAL**
Defined in Chart: **EWS**
Data-Type: **bit-array 23 downto 0**

Short Description: **System's input; comes from the sensor.**

Figure 3.2. A bit- array data-item in the Data Dictionary

Records

User-Defined Type: **RANGE**
Defined in Chart: **EWS**
Data-Type: **record**

Field Name: **LOW_LIMIT**	Field Type: **real**
Field Name: **HIGH_LIMIT**	Field Type: **real**

Data-Item: **LEGAL_RANGE**
Defined in Chart: **EWS**
Data-Type: **RANGE**

Data-Item: **FAULT_REPORT**
Defined in Chart: **EWS**
Data-Type: **record**

Field Name: **FAULT_TIME**	Field Type: **TIME**
Field Name: **FAULT_VALUE**	Field Type: **real**
Field Name: **FAULT_RANGE**	Field Type: **RANGE**

Figure 3.5. User-defined type **RANGE** in the Data Dictionary

Such groups are called **information-flow**.

Representation

- A flow-line originates from its **source activity**, and leads to its **target activity**:

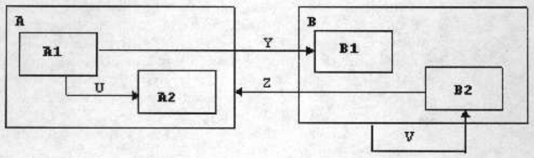


Figure 2.4. Flow of information among levels

- An arrow can be connected to a non-basic box, meaning it relates to **all the subboxes** within the box in question, see above the data flow lines labeled V and Z.
- Information flow SIGNAL in Figure 2.5 is declared in the Data Dictionary as in Figure 3.2 and is used in data processing.

Information-flow in Data Dictionary

Information flow COMMANDS in the Data Dictionary declared as below, is used to denote **control issues**.

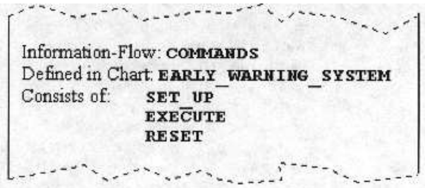


Figure 2.7. Information-flow COMMANDS in Data Dictionary

The number of lines in an activity chart can be reduced by grouping information elements into an **information-flow**, used to label a common flow line, e.g. COMMANDS consists of SET_UP, EXECUTE, RESET.

Flow Lines

- Flow lines may represent, e.g.,
  - parameter passing to procedures
  - passing of values of global variables
  - messages transferred in distributed systems
  - queues between tasks in real-time applications
  - signals flowing along physical links in hardware systems
- Flows can be continuous or discrete in time.

Flowing Elements

- Three types of information elements flow between activities: **events, conditions, data-items.**
- Their differences are in their **domain of values** and **timing characteristics**:

Events are instantaneous signals used for synchronization purposes, e.g., OUT_OF_RANGE in Figure 2.5.

Conditions are **persistent** signals that are either true or false, e.g., SENSOR_CONNECTED in Figure 2.5.

Data-item are **persistent** and may hold values of various types and structures, e.g., SIGNAL, a **bit-array**, or LEGAL_RANGE, a **record** with two fields of type **real**, HIGH_LIMIT and LOW_LIMIT.

Complex Information Structures

All three types of information elements can be arranged in array and record structures:

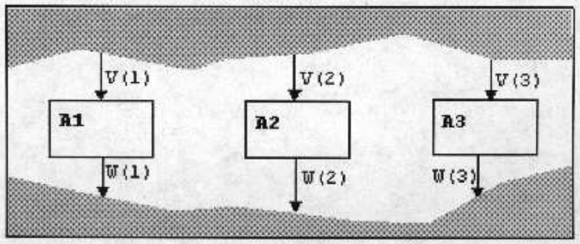


Figure 2.6. Array components labelling flow-lines

Data Stores

- There are no restrictions on the time that data reside on a flow line. Nevertheless it is often more natural to incorporate an explicit data store in the chart:

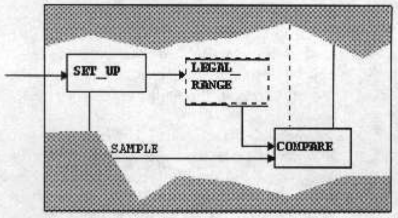


Figure 2.8. Data-store containing LEGAL_RANGE data

- A data item is defined in the Data Dictionary with the same name as the data store. Any structure given to a data item is inherited by the data store.

The Behavioral Functionality of Activities

- The behavior of subactivities of an activity chart is described by its **control activity**, whose function is to control their **sibling** activities (i.e., the other subactivities in the chart).
- Each activity may have **at most one** control activity.
- The control activity, depicted as a rectangle with rounded corners, cannot have subactivities.

Control Activity

A control activity may explicitly start and stop its sibling activities, i.e., EWS_CONTROL controls SET_UP, PROCESS_SIGNAL, and COMPARE:

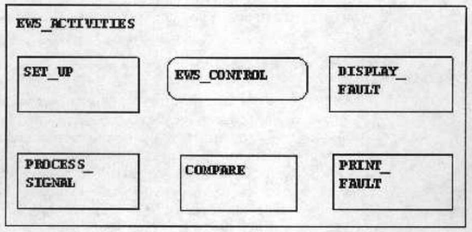
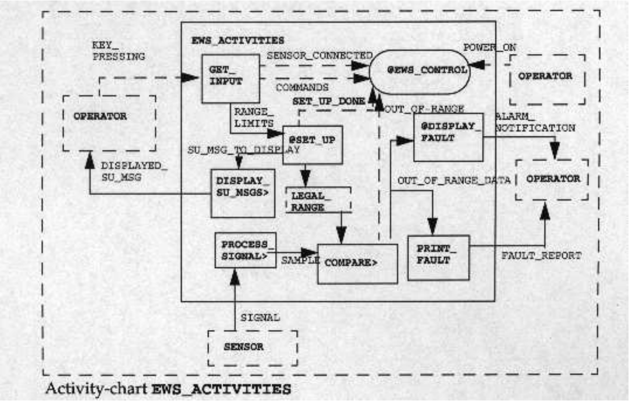


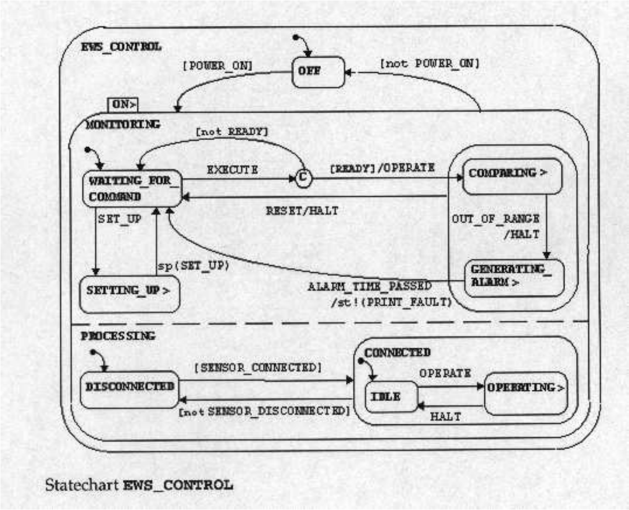
Figure 2.9. A control activity in an activity-chart

EWS-Activities



Activity-chart EWS_ACTIVITIES

EWS-Control

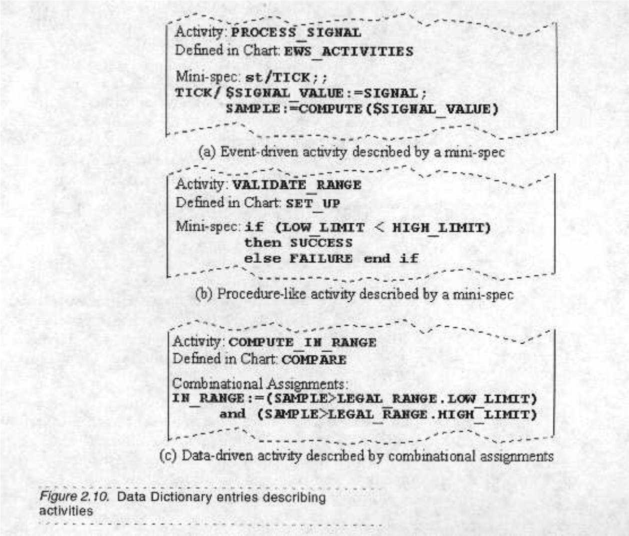


Statechart EWS_CONTROL

Activities in the Data Dictionary

- Every activity can be described more extensively in the Data Dictionary using **textual information.**
- **Basic activities** are described in the Data Dictionary by **executable textual descriptions**, specifying patterns of behavior.

EWS-Example



Activity: PROCESS_SIGNAL
Defined in Chart: EWS_ACTIVITIES

Mini-spec: st/TICK;;
TICK/ $SIGNAL_VALUE:=SIGNAL;
SAMPLE:=COMPUTE($SIGNAL_VALUE)

(a) Event-driven activity described by a mini-spec

Activity: VALIDATE_RANGE
Defined in Chart: SET_UP

Mini-spec: if (LOW_LIMIT < HIGH_LIMIT)
then SUCCESS
else FAILURE end if

(b) Procedure-like activity described by a mini-spec

Activity: COMPUTE_IN_RANGE
Defined in Chart: COMPARE

Combinational Assignments:
IN_RANGE:=(SAMPLE>LEGAL_RANGE.LOW_LIMIT)
and (SAMPLE>LEGAL_RANGE.HIGH_LIMIT)

(c) Data-driven activity described by combinational assignments

Figure 2.10. Data Dictionary entries describing activities

Connectors and Compound Flow-Lines

The data flow lines leaving activity COMPARE in Figure 2.5 can be drawn with a **joint connector** as below:

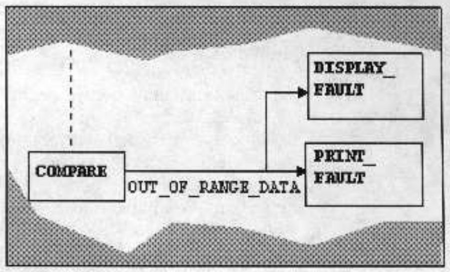


Figure 11. A joint connector (a fork construct)

Junction Connectors

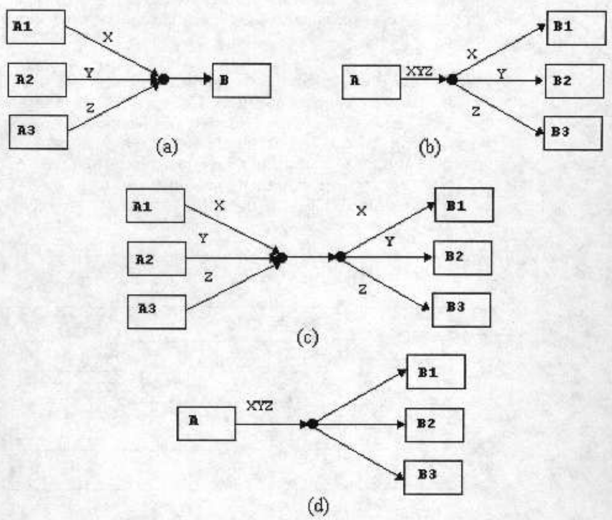


Figure 2.12. Junction connectors

Diagram Connectors

Diagram connectors are used when the source of a flow line is far from its target:

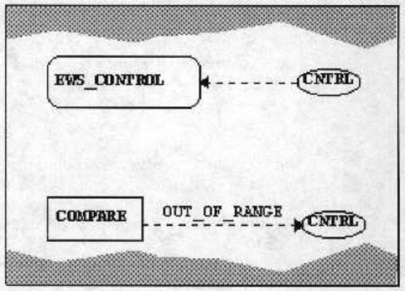


Figure 2.14. A diagram connector

Activity-Charts — Lesson IV

Describing the functional view of a system:

Activity-charts are used to depict the functional view of a system under development (SUD), "what the SUD does".

[HP98] Modeling Reactive Systems with Statecharts: The STATEMATE Approach, D. Harel, M, Politi. McGraw-Hill, 1998.

Last Session

Specification in a systems life cycle

- Identify several phases in the development life cycle of a system
- **Classic waterfall model**: requirements analysis, specification, design, implementation, testing, and maintenance.
- Other approaches center around prototyping, incremental development, reusable software, or automated synthesis.

Requirements Analysis

- Most proposals contain a requirements analysis phase. Specification errors and misconceptions should be discovered in that early phase.
- Correcting errors in later stages is extremely expensive.
- Special languages are therefore used in the requirements analysis phase to specify a model of the system, and special techniques are used to analyze it extensively.

System Model

- A good model is important for all participants in the system's development.
- Having a clear and executable model the functionality and behavior can be approved before investigating heavily in the implementation stages.
- The specification team uses modeling as the main medium for expressing ideas.

The early warning system

A system model constitutes a tangible representation of the system's conceptual and physical properties and serves as a vehicle for the specifier and designer to capture their thoughts.

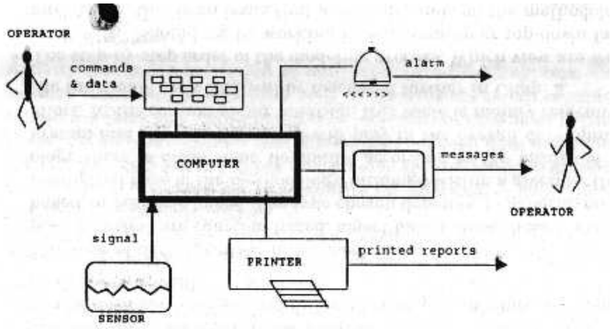


Figure 1.1 The early warning system (EWS).

STATEMATE

The modeling languages used in STATEMATE have been designed with several important properties in mind:

- to be intuitive and clear
- to be precise
- to be comprehensive
- to be fully executable

How to achieve these properties?

- To achieve clarity, elements of the model are represented graphically wher ever possible.
- For precision, all languages features have rigorous mathematical semantics
- Comprehension comes from the fact that the languages have the full expressive power needed to model all relevant issues, including the what, the when, and the how.
- For executability, the behavioral semantics is detailed and rigorous enough to enable the model to be executed (or be used to generate code).

Modeling Views

Building a model can be considered as a transition from ideas and informal descriptions to concrete descriptions that use concepts and predefined terminology.

Here, the descriptions used to capture the system specification are organized into three views: the **functional**, the **behavioral**, and the **structural**

The Three Views

Functional view : The functional view captures the “what”. It describes the system’s functions, processes, or objects, also called activities, thus pinning down its capabilities. This view includes the inputs and outputs of the activities.

Behavioral view : The behavioral view captures the “when”. It describes the system’s behavior over time, including the dynamics of activities, their control and timing behavior, the states and modes of the system, and the conditions and events that cause modes to change and other occurrences to take place.

Structural view : The structural view captures the “how”. It describes the subsystems, modules, or objects constituting the real system and the communication between them.

The Modeling Languages

The three views of a system model are described in our approach using three graphical languages.

- **Activity-charts** for the functional view,
- **Statecharts** for the behavioral view,
- and **Module-charts** for the structural view.
- Additional non-graphical information related to the views themselves and their inter-connections is provided in a **Data Dictionary**

Illustration

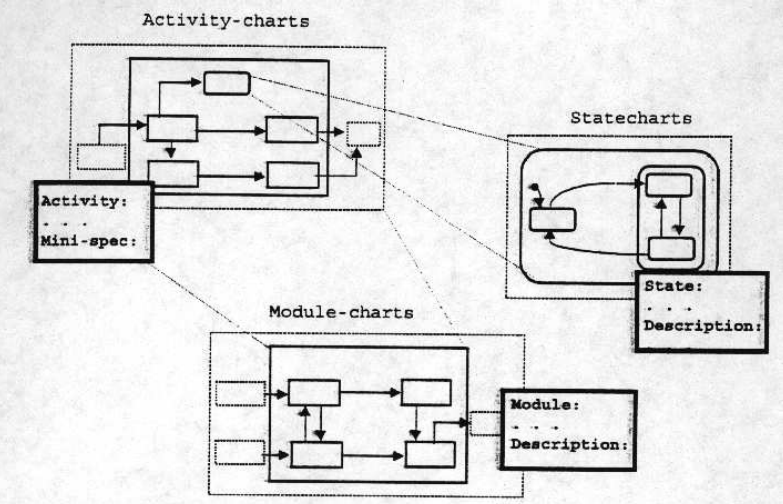


Figure 1.3 The modeling languages.

Activity-charts

Activity-charts can be viewed as multilevel data-flow diagrams. They capture functions, or activities, as well as data-stores, all organized into hierarchies and connected via the information that flows between them.

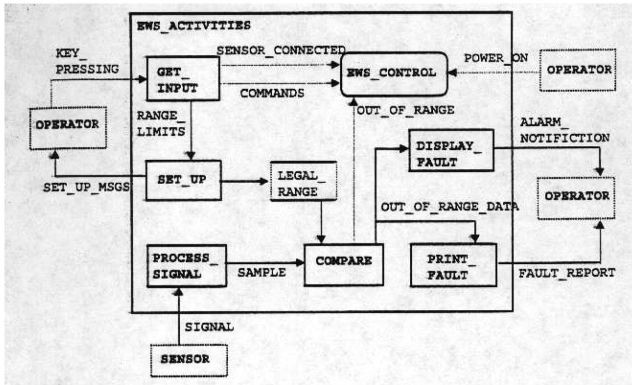


Figure 1.4 An activity-chart.

The STATEMATE toolset

STATEMATE has been constructed to “understand” the model and its dynamics. The user can then execute the specification by emulating the environment of the system under development and letting the model make dynamic progress in response.

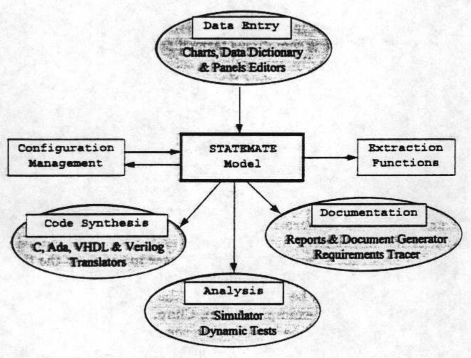


Figure 1.11 The STATEMATE toolset.

Configuration Management

Configuration managment

Basic idea of configuration management (CM) in the software development process is to guarantee the integrity (completeness and intactness) of the software product at any moment of the development

CM (cont’d)

Aims of CM:

- structure and discipline in the development process
- reusability of software

result of CM is

- better software quality and
- increased efficiency of the software development

CM is a management task that includes

- people responsible for it
- CM strategy/methods, plans
- support tools

Aspects of configuration management

- Identification: The imposed structure of the product provides access to parts of the product.
- Control: Product changes are authorized by a formal procedure that distinguishes different releases of the same product and its parts. Consistent releases constitute a baseline.
- Documentation: of status (releases, baselines).
- Verification: guarantees completeness and consistency
- Construction: of the product from its constituents
- process management: support the software life cycle.
- teamwork: several teams/developers of one product

CM informally

programming-in-the-many: ⇒ potential for confusion. CM is meant to decrease the confusion. CM must

- identify,
- organize, and
- control

changes by different developers. The aim of CM is to increase quality by avoiding errors.

Architecture of a CM system

- repository: to provide consistency, releases and baselines;
- workareas: parallel development/test and parallel (sic!) changes of the same parts of the software
- Makefiles: construction and dependency checks

Tasks of a CM system

Typical CM activities from the viewpoint of a developer (= user)

- check out current product parts
- build product from checked out parts (if available)
- check in modifications
- compare own version to one in the repository
- update to actual status
- change the structure of the product: add or remove parts.

Activity-Charts

System's Specification

- a hierarchy of functional components, called **activities**,
- what kind of information is exchanged between these activities and is manipulated by them,
- how this information flows,
- how information is stored, and
- how activities are **started and terminated**, i.e., **controlled**, if necessary, and whether activities are **continuous**, or whether they **stop by themselves**.

Hierarchical Data Flow Diagrams

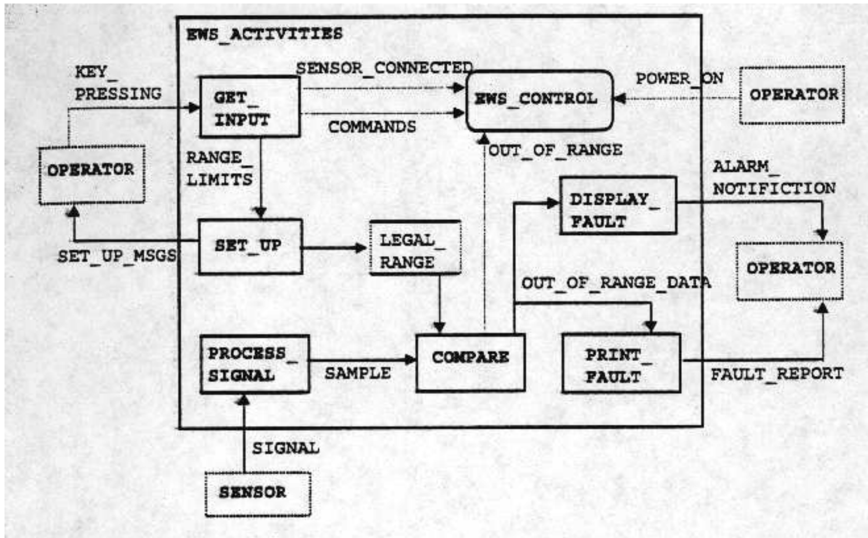


Figure 1.4 An activity-chart.

Functional decomposition of a System

The functional view of a system specifies the system's **capabilities**.
It does so in the context of the system's environment, that is, it defines the environment with which the system interacts and the interface between the two:

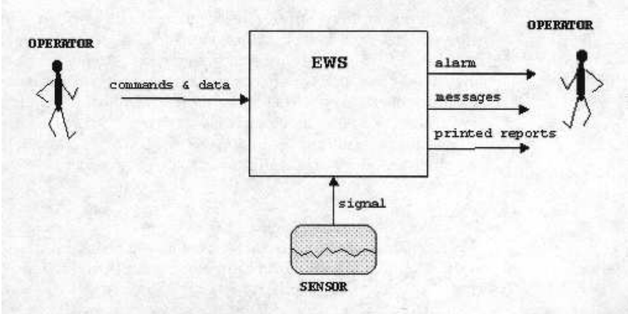


Figure 2.1. The context of the EWS

Structural View

This functional view does not address the physical and implementation aspects of the system; the latter is done in its **structural** view, i.e., its **module-chart**:

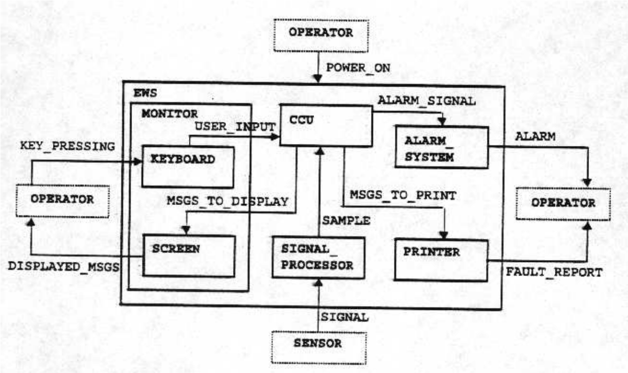


Figure 1.7 A module-chart.

Behavioral Aspects

Moreover it separates the dynamics and behavioral aspects of the SUD from its functional description. The former is done by its **behavioral** view, in its controlling Statecharts:

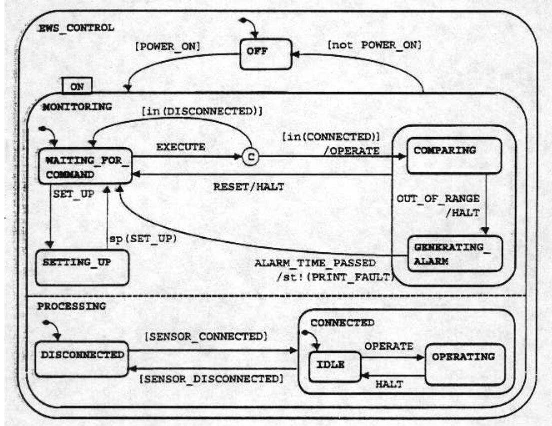


Figure 1.6 A statechart.

Example

The **functional view** tells whether a medical diagnosis system can monitor a patient's functions, and, if so, where it gets its input data and which functions have access to the output data.

The **behavioral view** tells under which conditions monitoring is started, whether it can be carried out parallel to temperature monitoring, and how the flow of control of the process of monitoring develops.

The **structural view** deals with the sensors, processors, monitors, software modules and hardware necessary to implement the monitoring system

The three views

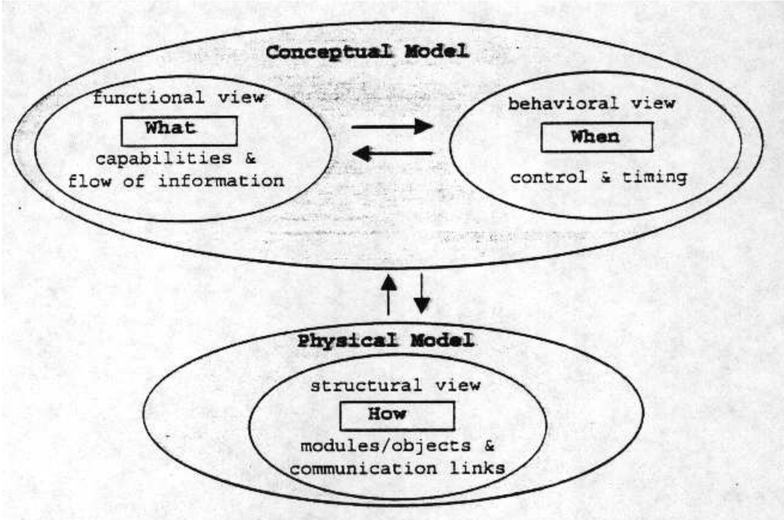


Figure 1.2 The three specification views.

Illustration

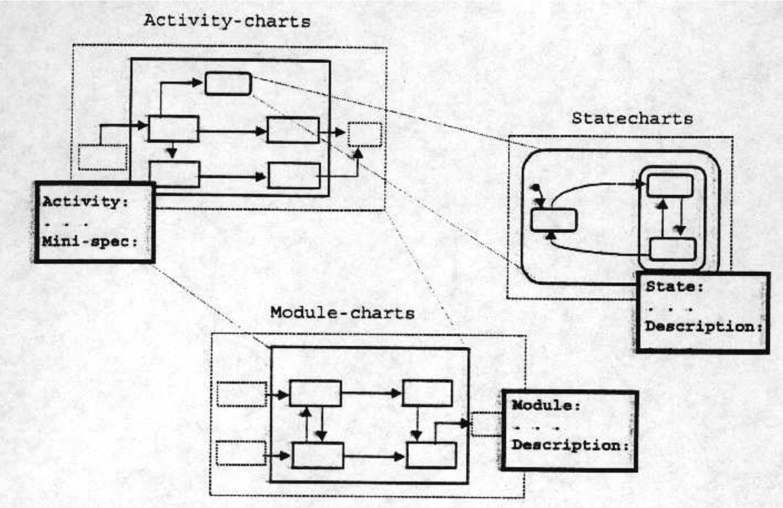


Figure 1.3 The modeling languages.

Functional Decomposition

In the Statechart approach, the functionality of a system is described by **functional decomposition**, by which a system is viewed as a collection of interconnected functional components, called **activities**, organized into a hierarchy.

EWS_ACTIVITIES

E.g., in the activity-chart EWS_ACTIVITIES, the SET_UP components can be decomposed leading to a multi-level decomposition of EWS_ACTIVITIES:

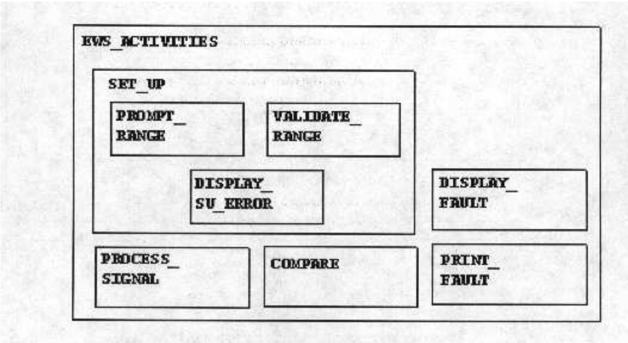


Figure 2.3. Multi-level decomposition of an activity

Functional Decomposition (cont'd)

- Each of the activities may be decomposed into subactivities repeatedly until the system is specified in terms of **basic activities**.
  There are specified using textual description (formal or informal), or code in a programming language, inside the Data Dictionary.
- The intended meaning of the functional decomposition is that **the capabilities of the parent activity are distributed between its subactivities.**

Functional Decomposition (cont'd)

- The **order** in which these subactivities are performed, and the **conditions** that cause their **activation** or **deactivation** are not represented in the functional view and are specified in the **behavioral view**, i.e., in the (one) statechart associated with the parent activity-chart.
- Activities can represent **objects, processes, functions, logical machines**, or any other kind of **functionally distinct entity**.
- In the following sections we'll confine ourselves to **function-based decomposition** of an activity-chart. We shall not discuss **object-based decomposition** (see Section 2.1.3 of Harel & Politi)

Function-based Decomposition

In function-based decomposition, the activities are (possibly reactive) functions.

The EWS receives a signal from an external sensor. When the sensor is connected, the EWS processes the signal and checks if the resulting value is within a specified range. If the value of the processed signal is out of range, the system issues a warning message on the operator display and posts an alarm. If the operator does not respond to this warning within a given time interval, the system prints a fault message on a printing facility and stops monitoring the signal. The range limits are set by the operator. The system becomes ready to start monitoring the signal only after the range limits are set. The limits can be re-defined after an out-of-range situation has been detected, or after the operator has deliberately stopped the monitoring.

Function-based Decomposition (cont'd)

Next we decompose this narrative to describe its functionality:

- The EWS receives a signal from an external sensor.
- It samples and processes the signal continuously, producing some result.
- It checks whether the value of the result is within a specified range that is set by the operator.
- If the value is out of range, the system issues a warning message on the operator display and posts an alarm.
- If the operator does not respond within a given time interval, the system prints a fault message on a printing facility and stops monitoring the signal.

Function-based Decomposition (cont'd)

Thirdly, we identify the various functions that are described by there requirements:

SET_UP: receives the range limits from the operator.

PROCESS_SIGNAL: reads the "raw" signal from the sensor and performs some processing to yield a value that is to be compared to the range limits.

COMPARE: compares the value of the processed signal with the range limits.

DISPLAY_FAULT: issues a warning message on the operator display and posts an alarm.

PRINT_FAULT: prints a fault message on the printing facility.

Function-based Decomposition (cont'd)

Notice that this description also contains info about handled data. An activity may **transform** its input into output to be consumed by other functions, which are **internal** or **external** to the system:

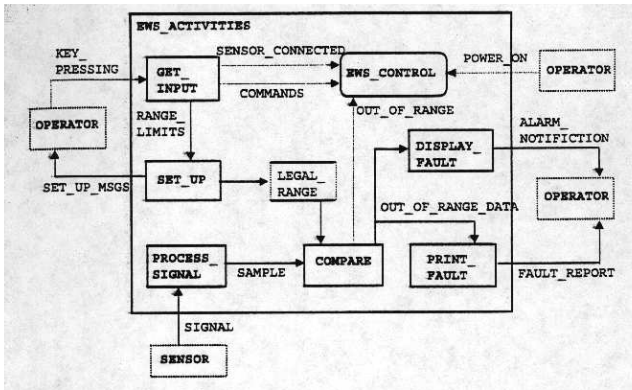


Figure 1.4 An activity-chart.

System Context

One of the first decisions to be made when developing a system involves its **boundaries**, or, **context**. I.e., one must determine which entities are part of the environment of a system, and how they communicate with the system. The latter are called **external activities** of the system.

EWS-Example

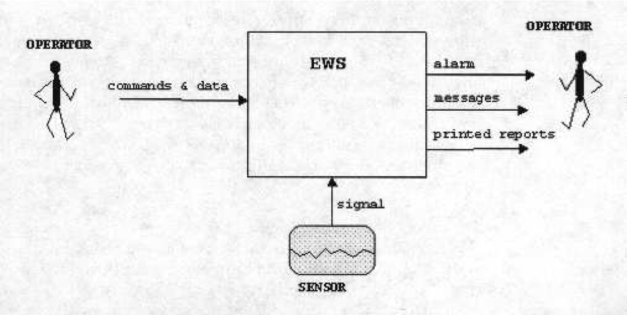


Figure 2.1. The context of the EWS

Notice that for the EWS one might have chosen for the printer to be external, leading to printer as external activity.

Different occurrences of the same entity (here: operator) denote the same entity; these are multiplicated of ease of drawing.

Decomposition process

The functional view is specified by **Activity-charts**, together with a **Data Dictionary** that contains additional information about the elements appearing in the charts, e.g., about their basic activities.

Activities and their representation

We continue the functional decomposition of the EWS, started with:

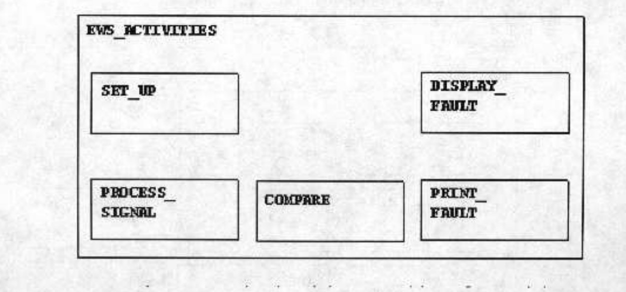


Figure 2.2. First level decomposition of an activity

This activity chart contains one top-level box, representing the **top-level activity** of the chart.

Top-Down Development

On their turn, the activities appearing above can be decomposed themselves, as SET_UP:

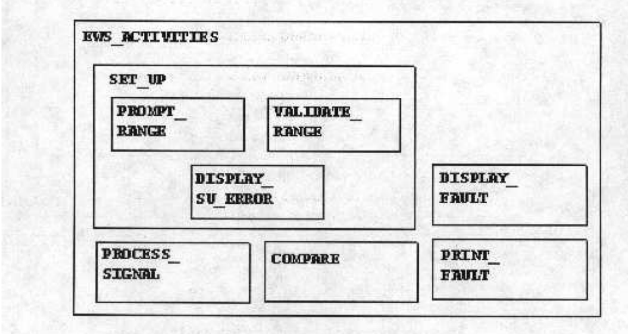


Figure 2.3. Multi-level decomposition of an activity

Some terminology

- EWS_ACTIVITIES is called **top-level activity**
- EWS_ACTIVITIES is also called **parent activity** of SET_UP, COMPARE, etc., which are called **descendants** of EWS_ACTIVITIES, as are the subactivities PROMPT_RANGE etc. of SET_UP, who have SET_UP and EWS_ACTIVITIES as **ancestor.**

Each activity has a corresponding item in the Data Dictionary, which may contain additional information.

Flow of Information between Activities

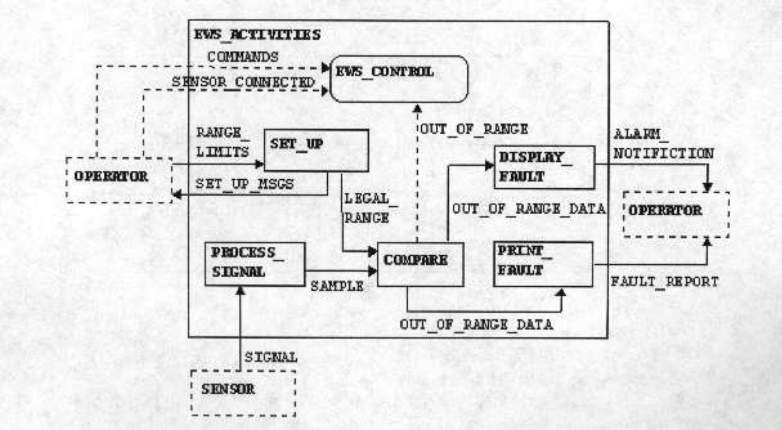


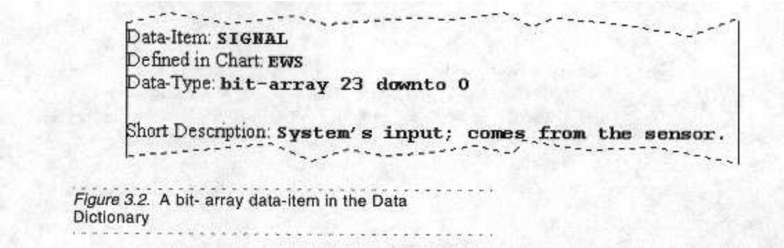
Figure 2.5. **EWS_ACTIVITIES**, its environment and flow of information

Information Flow in EWS

- OPERATOR and SENSOR are external activities, drawn using dotted lines.
- Different occurrences of OPERATOR refer to the same entity.
- Solid arrows denote **data-flow-lines** between activities.
- Control of EWS_ACTIVITIES is handled in its **control activity chart** EWS_CONTROL, a statechart (drawn using rounded corners).
- Dotted arrows denote **control-flow-lines**, carrying info or signals used in making **control decisions**.

Flow lines

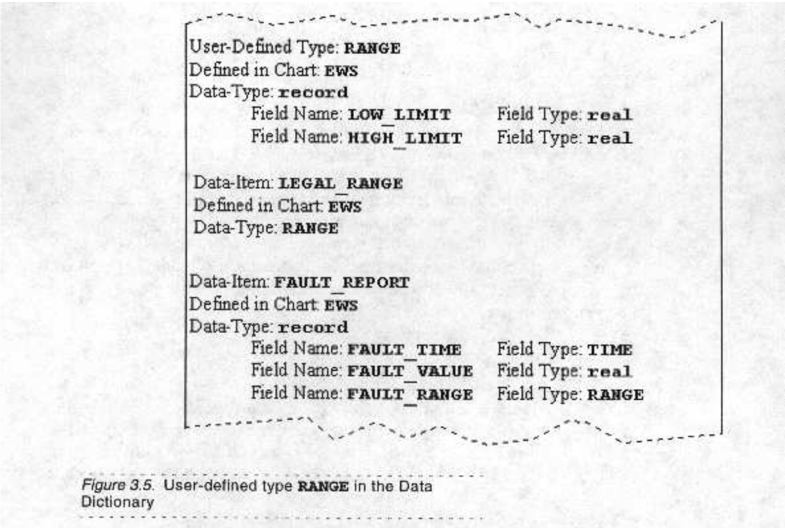
A label on a flow line denotes either a single information element that flows along the line, i.e., a **data-item**, **condition**, or **event** or a group of such elements, as in, e.g.:


Data-Item: **SIGNAL**
Defined in Chart: **EWS**
Data-Type: **bit-array 23 downto 0**

Short Description: **System's input; comes from the sensor.**

Figure 3.2. A bit- array data-item in the Data Dictionary

Records


User-Defined Type: **RANGE**
Defined in Chart: **EWS**
Data-Type: **record**
Field Name: **LOW_LIMIT** Field Type: **real**
Field Name: **HIGH_LIMIT** Field Type: **real**

Data-Item: **LEGAL_RANGE**
Defined in Chart: **EWS**
Data-Type: **RANGE**

Data-Item: **FAULT_REPORT**
Defined in Chart: **EWS**
Data-Type: **record**
Field Name: **FAULT_TIME** Field Type: **TIME**
Field Name: **FAULT_VALUE** Field Type: **real**
Field Name: **FAULT_RANGE** Field Type: **RANGE**

Figure 3.5. User-defined type **RANGE** in the Data Dictionary

Such groups are called **information-flow**.

Representation

- A flow-line originates from its **source activity**, and leads to its **target activity**:

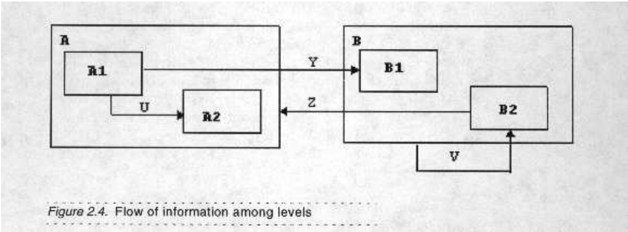


Figure 2.4. Flow of information among levels

- An arrow can be connected to a non-basic box, meaning it relates to **all the subboxes** within the box in question, see above the data flow lines labeled V and Z.
- Information flow SIGNAL in Figure 2.5 is declared in the Data Dictionary as in Figure 3.2 and is used in data processing.

Information-flow in Data Dictionary

Information flow COMMANDS in the Data Dictionary declared as below, is used to denote **control issues**.

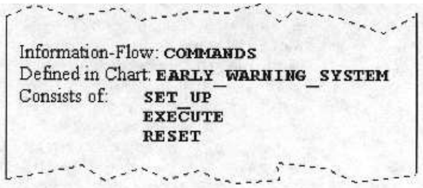

Information-Flow: COMMANDS
Defined in Chart: EARLY_WARNING_SYSTEM
Consists of: SET_UP
EXECUTE
RESET

Figure 2.7. Information-flow COMMANDS in Data Dictionary

The number of lines in an activity chart can be reduced by grouping information elements into an **information-flow**, used to label a common flow line, e.g. COMMANDS consists of SET_UP, EXECUTE, RESET.

Flow Lines

- Flow lines may represent, e.g.,
  - parameter passing to procedures
  - passing of values of global variables
  - messages transferred in distributed systems
  - queues between tasks in real-time applications
  - signals flowing along physical links in hardware systems
- Flows can be continuous or discrete in time.

Flowing Elements

- Three types of information elements flow between activities: **events, conditions, data-items.**
- Their differences are in their **domain of values** and **timing characteristics**:

Events are instantaneous signals used for synchronization purposes, e.g., OUT_OF_RANGE in Figure 2.5.

Conditions are **persistent** signals that are either true or false, e.g., SENSOR_CONNECTED in Figure 2.5.

Data-item are **persistent** and may hold values of various types and structures, e.g., SIGNAL, a **bit-array**, or LEGAL_RANGE, a **record** with two fields of type **real**, HIGH_LIMIT and LOW_LIMIT.

Complex Information Structures

All three types of information elements can be arranged in array and record structures:

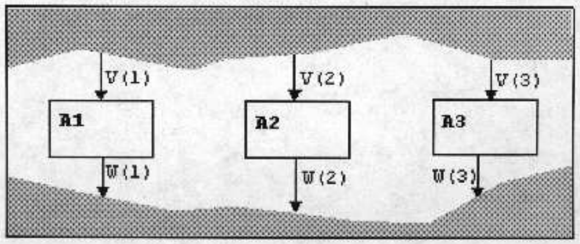


Figure 2.6. Array components labelling flow-lines

Data Stores

- There are no restrictions on the time that data reside on a flow line. Nevertheless it is often more natural to incorporate an explicit data store in the chart:

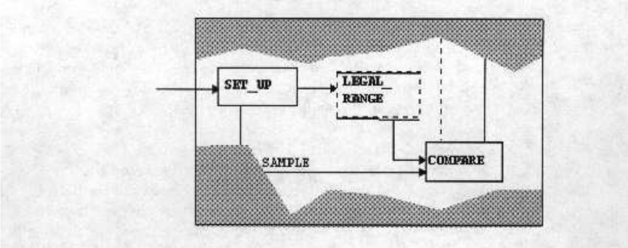


Figure 2.8. Data-store containing LEGAL_RANGE data

- A data item is defined in the Data Dictionary with the same name as the data store. Any structure given to a data item is inherited by the data store.

The Behavioral Functionality of Activities

- The behavior of subactivities of an activity chart is described by its **control activity**, whose function is to control their **sibling** activities (i.e., the other subactivities in the chart).
- Each activity may have **at most one** control activity.
- The control activity, depicted as a rectangle with rounded corners, cannot have subactivities.

Control Activity

A control activity may explicitly start and stop its sibling activities, i.e., EWS_CONTROL controls SET_UP, PROCESS_SIGNAL, and COMPARE:

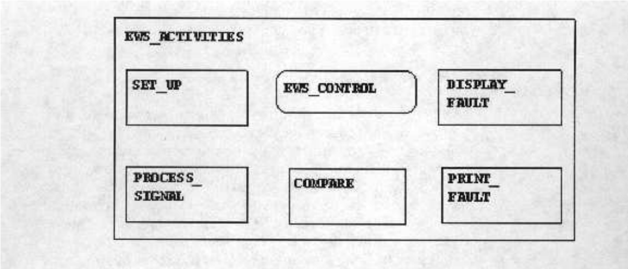
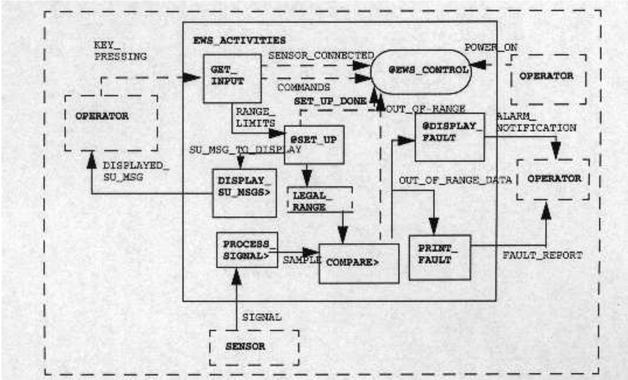


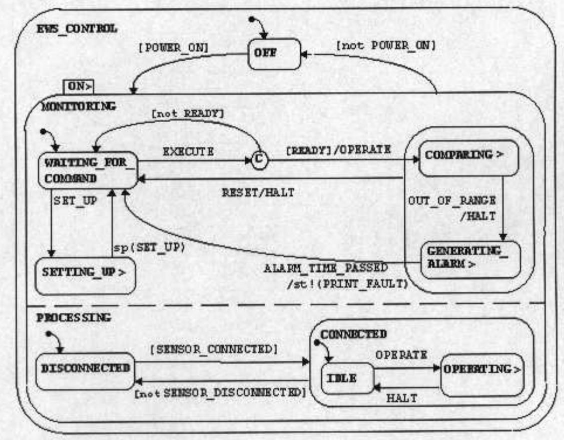
Figure 2.9. A control activity in an activity-chart

EWS-Activities



Activity-chart EWS_ACTIVITIES

EWS-Control

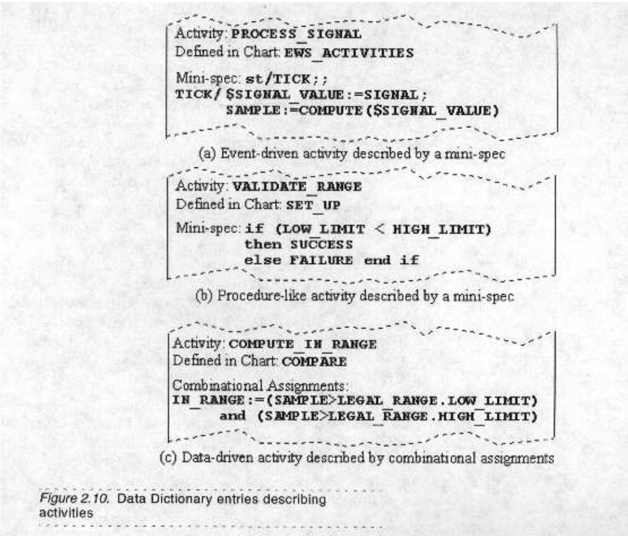


Statechart EWS_CONTROL

Activities in the Data Dictionary

- Every activity can be described more extensively in the Data Dictionary using **textual information**.
- **Basic activities** are described in the Data Dictionary by **executable textual descriptions**, specifying patterns of behavior.

EWS-Example



Activity: PROCESS_SIGNAL
Defined in Chart: EWS_ACTIVITIES
Mini-spec: st/TICK;;
TICK/ $SIGNAL_VALUE:=SIGNAL;
SAMPLE:=COMPUTE($SIGNAL_VALUE)

(a) Event-driven activity described by a mini-spec

Activity: VALIDATE_RANGE
Defined in Chart: SET_UP
Mini-spec: if (LOW_LIMIT < HIGH_LIMIT)
then SUCCESS
else FAILURE end if

(b) Procedure-like activity described by a mini-spec

Activity: COMPUTE_IN_RANGE
Defined in Chart: COMPARE
Combinational Assignments:
IN_RANGE:=(SAMPLE>LEGAL_RANGE.LOW_LIMIT)
and (SAMPLE>LEGAL_RANGE.HIGH_LIMIT)

(c) Data-driven activity described by combinational assignments

Figure 2.10. Data Dictionary entries describing activities

Connectors and Compound Flow-Lines

The data flow lines leaving activity COMPARE in Figure 2.5 can be drawn with a **joint connector** as below:

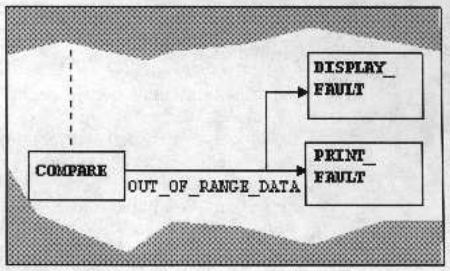


Figure 11. A joint connector (a fork construct)

Junction Connectors

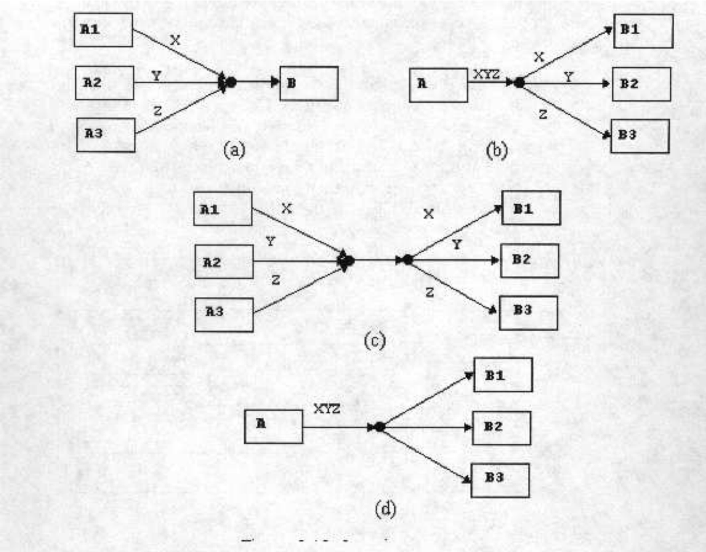


Figure 2.12. Junction connectors

Diagram Connectors

Diagram connectors are used when the source of a flow line is far from its target:

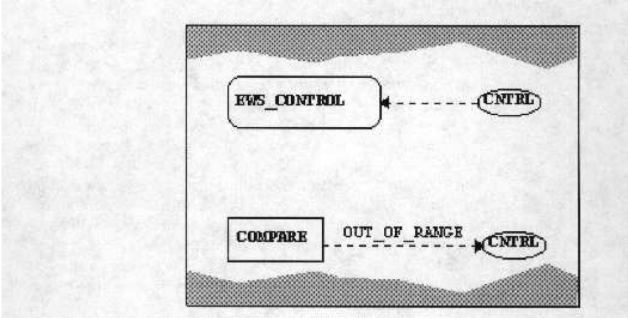


Figure 2.14. A diagram connector

Activity-Charts and Statecharts — Lesson V

We discuss the actions used by a statechart to control activities, and the events and conditions used by it to sense their status.

[HP98] Modeling Reactive Systems with Statecharts: The STATEMATE Approach, D. Harel, M, Politi. McGraw-Hill, 1998.

SCL programs

Skeleton

```
PROGRAM  template;

CONSTANT
 INTEGER step_counter := 0;
VARIABLE
 INTEGER I := 45;
 GLOBAL FILE f1;

INIT
END INIT;

SET BREAKPOINT [STEP] DO
END BREAKPOINT;

BEGIN
END;
END.
```


Declaration

```
-- CONSTANT
--%% To declare constants remove the comment sign in the previous line
--%% and declare their types as in the example in the next several lines.
--%%    INTEGER step_counter := 0;

-- VARIABLE
--%% In this section you declare variables
--%% and their types as in the example in the next several lines.
--%%    INTEGER I := 45;
--%%    GLOBAL FILE f1;
```


Init

```
-- INIT
--%% In this section you place SCL statements to be executed once,
--%% each time the SCP is invoked.
-- END INIT;


INIT
time_to_change:=0;
open(fout,'/tmp/klimatest.log', output);
write(fout,'Juhu','\n')
END INIT;
```


Breakpoints

```
-- SET BREAKPOINT [STEP] DO
--%% In this section you put statements to be executed conditionally,
--%% at each simulation step.  Duplicate this structure for each
--%% breakpoint definition.
--%% The condition STEP may be replaced by other condition/event expressions
-- END BREAKPOINT;

set breakpoint neue_temperatur=> every 1 do
  if (time_to_change <= cur_clock) then
    temp:=rand_iuniform(-20,40);
    write('Temperature changed to ',temp,' at ',cur_clock,'\n');
    time_to_change:=rand_iuniform(20,120)+cur_clock;
    write('Next change at ',time_to_change,'\n');
  end if;
end breakpoint;
```

Body

```
-- BEGIN
--%% This is the Main Section, in which you place any SCL statements,
--%% including Go statements.
--%% These statements are executed sequentially.
-- END;

BEGIN
write('Simulation started at: ',cur_clock,'\n');
while true loop
  go step;
end loop;
```


Connections between Activity-Charts and Statecharts

Dynamics in the Functional Decomposition

The activities participating in the functional decomposition are not necessarily always active. In most kinds of systems many of the activities have limited periods in which they are active.

Examples

Some examples with different dynamics:

- **Procedures and functions** in software programs start when they are "called" and stop upon completion.
- In **multi-tasking or multi-processing systems**, tasks are invoked, do their job, and then are "killed" or "kill" themselves.
- Tasks with **lower priority** maybe interrupted or delayed when a mission of higher priority arrives.
- **Interactive user interface** is specified by "callback functions".

EWS Example

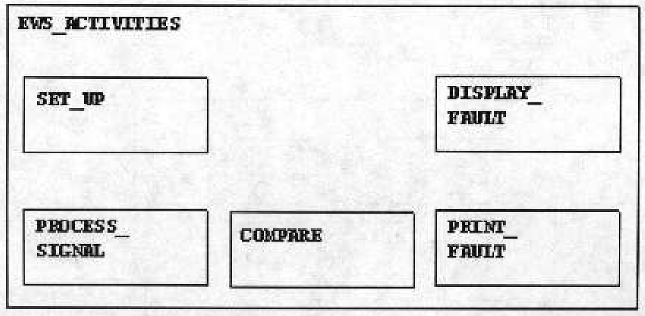


Figure 2.2. First level decomposition of an activity

EWS Example (cont'd)

Dynamic and timing issues related to the activities in the EWS example:

SET_UP: activated by an explicit request of the operator, terminates on its own.

COMPARE: starts with the EXECUTE command and stops with the OUT_OF_RANGE event or the RESET command.

PROCESS_SIGNAL: active when the COMPARE activity is active.

DISPLAY_FAULT: starts with the OUT_OF_RANGE event and is stopped by the operator or after a predefined time period.

PRINT_FAULT: starts when the time period is passed and terminates on its own.

Specifying the Dynamics

- Obviously, merely listing the activities and their connections, as is done in the functional view, is not sufficient. We have to specify the dynamics of controlling these activities, including the starting and stopping of the subactivities of a non-basic activity.
- The order in which the functional and behavioral views and their connections are developed depends on the nature of the system and on the specification methodology.

Methodology

- One can start by carrying out a functional decomposition in activity-charts, and then add the timing and other dynamic information in statecharts to capture behavior.
- In contrast, it is possible to start by using statecharts to describe the system's modes of operation and/or a collection of use-cases, and then construct an activity-chart from the activities performed in these modes or scenarios.

Dynamics of Activities

In order to capture the dynamic behavior of non-basic activities, our models employ control activities that are associated with statecharts.

Statecharts in the functional view

When a non-basic activity that contains a control activity starts its execution, the statechart associated with that control activity becomes active, i.e., the system enters the top level state of this statechart.

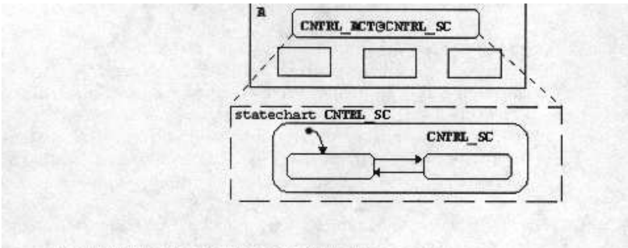


Figure 7.1. Associating a statechart with a control activity

Control Activities

An activity with a reactive behavior pattern can be described by a statechart even though it is not further decomposed, so that it has no subactivities to control:

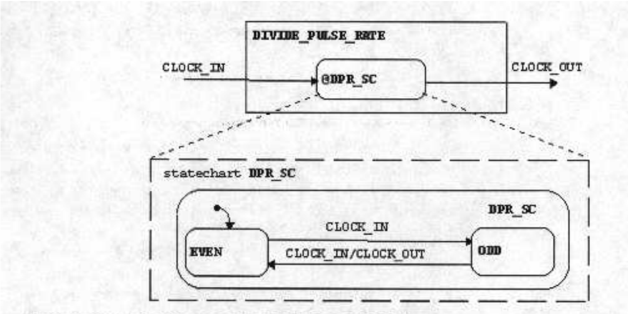


Figure 7.2. A statechart describing a simple activity

Control Activities (cont'd)

In some cases, the control behavior of an activity can be captured by static reactions alone. Then, the controlling statechart will consist of a single top-level state with the static reactions given in its Data Dictionary entry.

Note: While the controlling statechart may consume and produce external (control and data) information, its interface does not appear in the statechart itself.

Termination Type of an Activity

We distinguish between activities that have **self-termination** and those that have **controlled-termination**.

If a self-terminating activity has a control activity, then the corresponding statechart must contain a **termination connector**.

Termination Connector

It is considered a final state; in particular it has no exits:

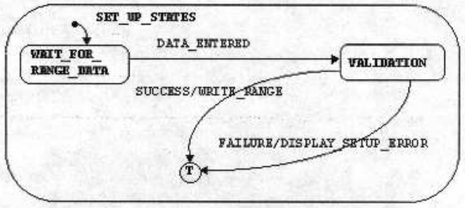


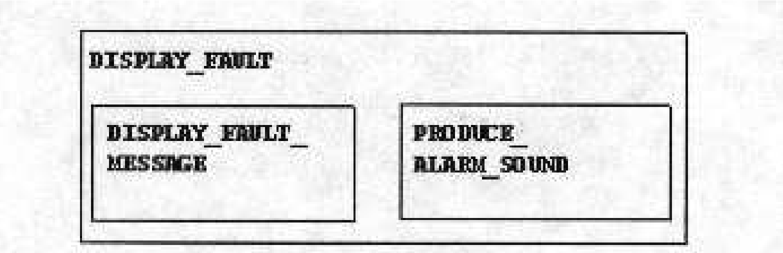
Figure 7.3. Termination connector in SET-UP's statechart

Upon entering this connector, the statechart “stops”, its parent activity becomes deactivated, and the event STOPPED(A) occurs.

When a non-basic activity stops, all its subactivities stop immediately too.

Perpetual Activities

Sometimes there is no control activity needed:



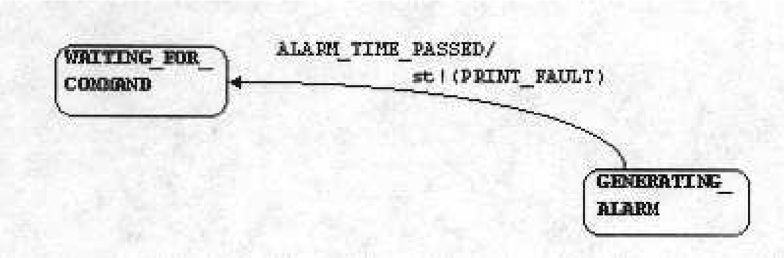
All the subactivities start when the parent activity starts, and they all stop when it stops.

Controlling the activities

How does the controlling statechart affect and sense the status of its sibling activities?

Starting and Stopping Activities

The main mechanism that statecharts use to control activities is the ability to start and stop them explicitly:



Examples

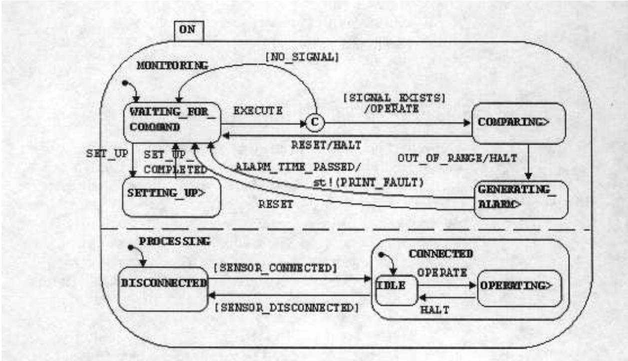


Figure 7.6. States marked as having entering and exiting reactions

The control activity can control only its sibling activities. Therefore, all actions that appear in its statchart may refer to the sibling activities only.

Sensing the status of Activities

The statchart that describes a control activity is not limited to causing activities to start and stop. It can also sense whether such happenings have indeed taken place. Specifically, the control activity can sense the events STARTED(A) and STOPPED(A), and the condition ACTIVE(A).

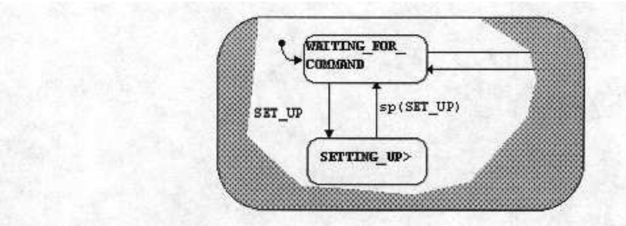


Figure 7.7. An event signifying termination of an activity

The events and conditions in the describing statechart are allowed to refer only to the sibling activities.

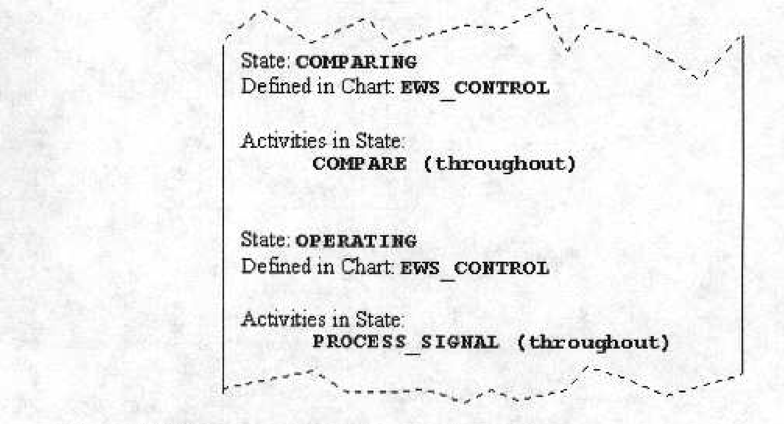
Activities in States

Often, we wish an activity A to start when a certain state S is entered, and to stop when S is exited.

This can be specified by associating the action ST!(A) with the entering event NS and SP!(A) with the exiting event XS in the Data Dictionary.

Activities Throughout and Within States

Another more compact way is to specify that A is **active throughout** S:


State: COMPARING
Defined in Chart: EWS_CONTROL

Activities in State:
COMPARE (throughout)

State: OPERATING
Defined in Chart: EWS_CONTROL

Activities in State:
PROCESS_SIGNAL (throughout)

Figure 7.8. Activities active throughout states in the Data Dictionary

Suspending and Resuming Activities

In addition to being able to start and stop activities, control activities can cause an activity to “freeze”, or **suspend**, its activation, and to later **resume** from where it stopped.
The relevant actions are SUSPEND(A) and RESUME(A).
Associated with these actions is the condition HANGING(A).

Suspension

Suspension may be used, for example, when we want to interrupt the progress of an activity in favor of another activity with higher priority:

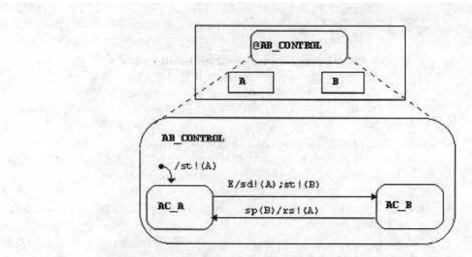


Figure 7.10. Suspending and resuming activities

The event E causes A to be suspended, while the preferred activity B is carried out to completion, at which time A is resumed.

Comparison with History Entrance

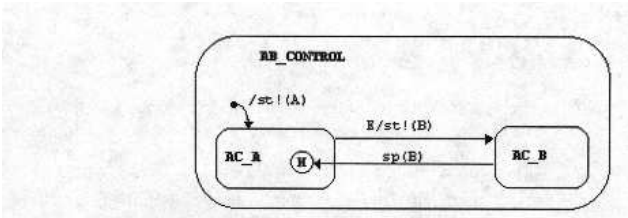


Figure 7.11. History entrance vs. resume activity

When A is active throughout AC_A the action is started again.

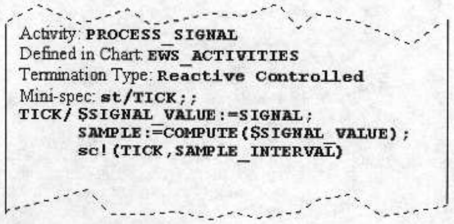
On the other hand, not stopping A would allow A to react on events while B is active.

Specifying Behavior of Basic Activities

When carrying out functional decomposition, the lower building blocks of the description are the basic activities, those that require no further breakup.
Basic activities may have additional textual descriptions in the Data Dictionary and are marked by a “>”.

Reactive Mini-Specs

In some cases the behavior of a basic activity can be described by a collection of reactions, consisting of triggers and their implied actions.
A reactive mini-spec is a list of reactions of the form TRIGGER/ACTION, separated by a double semi-colon (;;).



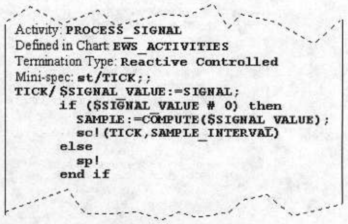
Activity: **PROCESS_SIGNAL**
Defined in Chart: **EWS_ACTIVITIES**
Termination Type: **Reactive Controlled**
Mini-spec: **st/TICK;;**

```
TICK/ $SIGNAL_VALUE:=SIGNAL;
        SAMPLE:=COMPUTE($SIGNAL_VALUE);
        sc!(TICK,SAMPLE_INTERVAL)
```

Figure 7.12. A reactive mini-spec in the Data Dictionary

Reactive Mini-Specs (cont’d)

A reactive mini-spec can be attached to both self-terminating or controlled-terminating activities.



Activity: **PROCESS_SIGNAL**
Defined in Chart: **EWS_ACTIVITIES**
Termination Type: **Reactive Controlled**
Mini-spec: **st/TICK;;**

```
TICK/ $SIGNAL_VALUE:=SIGNAL;
      if ($SIGNAL_VALUE # 0) then
        SAMPLE:=COMPUTE($SIGNAL_VALUE);
        sc!(TICK,SAMPLE_INTERVAL)
      else
        sp!
      end if
```

Figure 7.13. The **stop** action in a mini-spec

It is important to remember that states and activities cannot be referred to in the mini-spec. All the activities and states of the model are beyond the scope of an individual mini-spec.

Procedure-Like Mini-Specs

Often an activity can be described as a sequence of actions, possibly with conditional branching and iterations. Such activities are called **procedure-like**. They are active for a single step only. Therefore, such activities are always self-terminating.

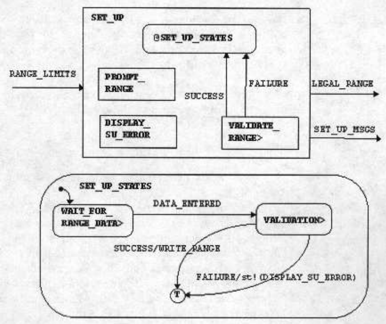


Figure 7.14. **SET-UP** activity and controlling statechart

Corresponding Mini-Spec

```
Activity: VALIDATE_RANGE
Defined in Chart: SET_UP
Termination Type: Procedure-Like
Mini-spec: if LOW_LIMIT < HIGH_LIMIT then
   SUCCESS
else
   FAILURE
end if
```

Figure 7.15. A procedure-like mini-spec in the Data Dictionary

Combinational Assignments

Another typical behavior for an activity is that of a **data-driven** pattern. The activity is continuously ready to perform some calculations whenever the input changes its value.

```
Activity: COMPUTE_IN_RANGE
Defined in Chart: COMPARE
Termination Type: Reactive Controlled
Combinational Assignments:
IN_RANGE:= (SAMPLE > LEGAL_RANGE.LOW_LIMIT) and
           (SAMPLE < LEGAL_RANGE.HIGH_LIMIT)
```

Figure 7.16. Combinational assignments in the Data Dictionary

Communication between Activities

Specifying the communication between activities consists of the what and the when, just like for other parts of the specification.
The what is described by the flow-lines in the activity-charts and relevant parts of the Data Dictionary. The when is to be specified by the behavioral parts of the model, i.e., the statecharts and mini-specs.

Communication and Synchronization Issues

Functional components in systems communicate between themselves in order to pass along information and to help synchronize their processing. A number of attributes characterize the various communication mechanisms.

Attributes

Communication can be

- **instantaneous** , meaning that it is lost when not consumed immediately, or

  persistent , meaning that it stays around until it gets consumed.
- **synchronous** , i.e., the sender waits for an acknowledgment, or

  asynchronous , i.e., there is no waiting on the part of the sender
- **directly addressed** , i.e., the target is specified, or sent by

  broadcasting

Controlling the Flow of Information

In the following figure X is specified to flow between activities A and B:

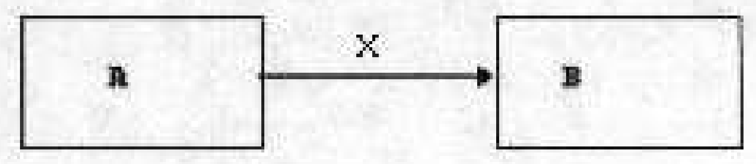


Figure 8.1. An information element flowing between activities

Flow of Information

If X is an event we may have the following situation:

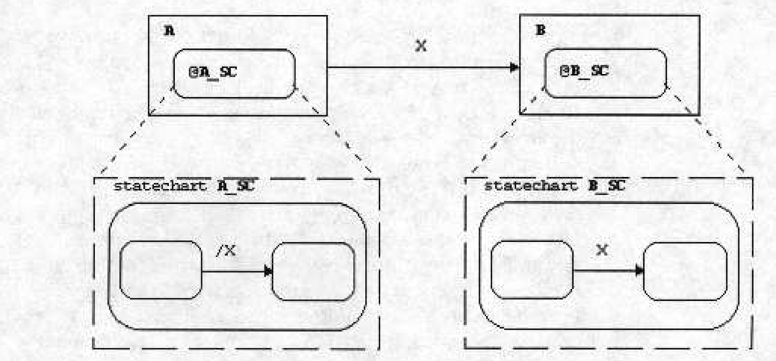


Figure 8.2. Producing and consuming an event

If X is a condition or data-item modified by A, B could sense the value or the change of the value (X, TR(X), WR(X)).

Examples of Communication Control

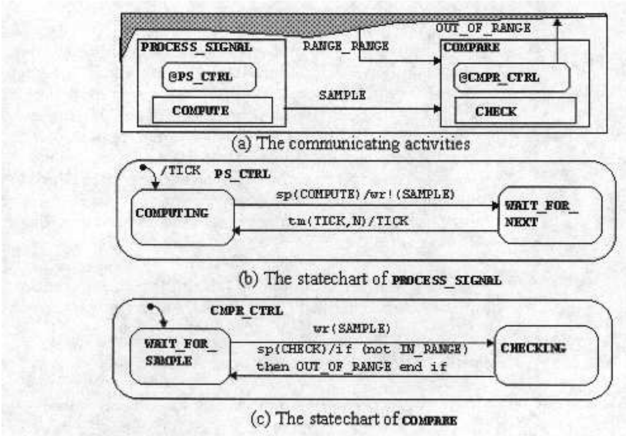


Figure 8.4. Communication between periodic activities

Message Passing

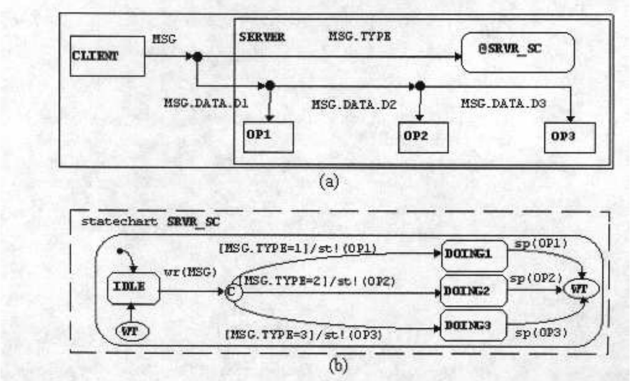


Figure 8.5. Server responding to three service requests

Activities Communicating Through Queues

Queuing facilities for messages are virtually indispensable in modeling multi-processing environments, and especially multiple client-server systems.
We want to have:

- ability to sent unlimited number of messages to the same address, while the receiver is not always in a position to accept them,
- no message is consumed before one that was sent earlier,
- possibility for concurrently active components to write messages to the same address at the same moment
- possibility for concurrently active components to read different messages to the same address at the same moment

Queues and their operations

A queue is an ordered, unlimited collection of data-items, all of the same data type. The queue is usually shared among several activities, which can employ special actions to add elements to the queue and read and remove elements from it.

- **q_put(Q,D)** add the value of expression D to the queue
- **q_urgent_put(Q,D)** add the value of expression D to the head of the queue
- **q_get(Q,D,S)** extract the element at the head of Q and place it in D
- **q_peek(Q,D,S)** same as above without removing the element from Q
- **q_flush(Q)** clears Q totally

Combination with Data Stores

The following figure illustrates the order in which operations on a queue are performed during a step:

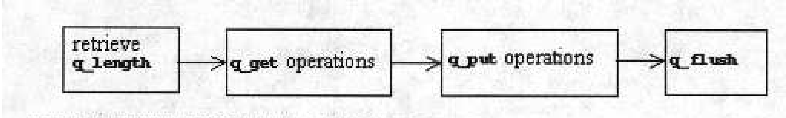


Figure 8.6. Operations on a queue during a step

Queues can be associated with data stores just like data-items of other types can.

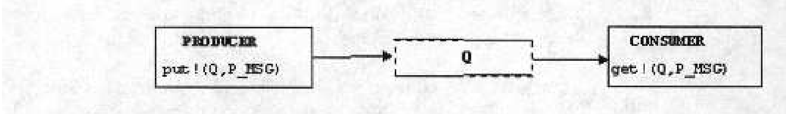


Figure 8.7. A queue associated with a data-store

Example

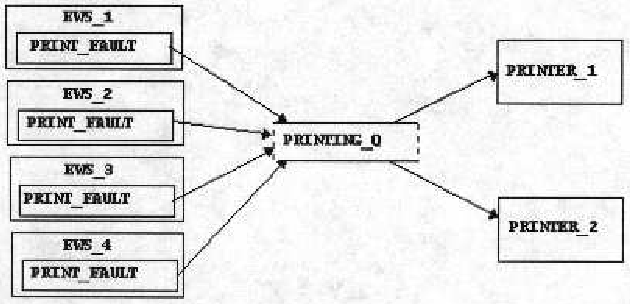


Figure 8.8. Multiple clients served by multiple servers via a queue

Example

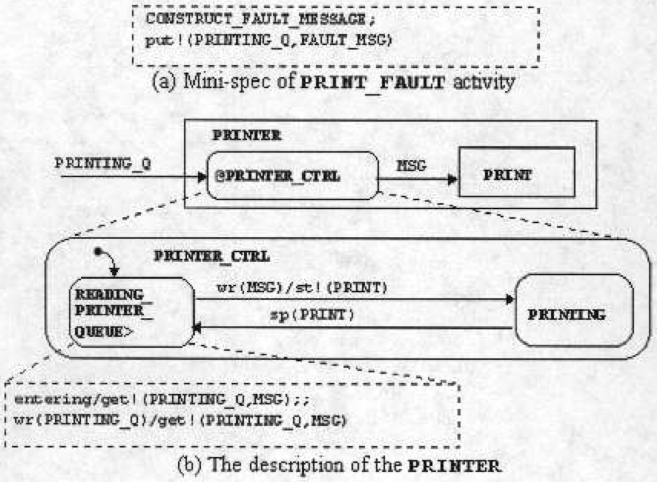


Figure 8.9. Writing and reading messages from a queue

Conditions and Events Related to States

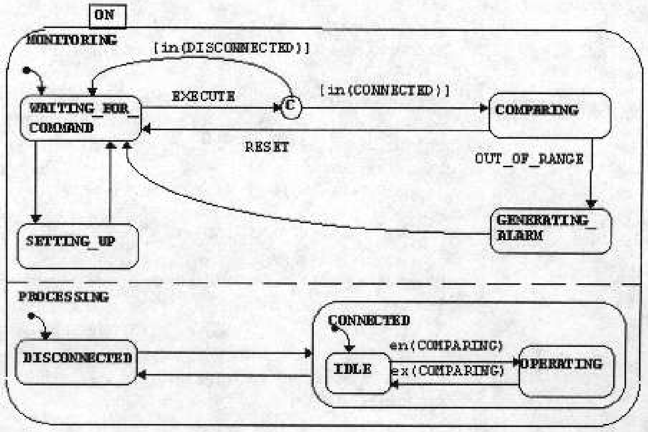


Figure 4.15. Conditions and events related to states

Condition Connector

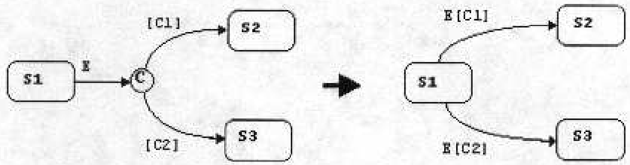


Figure 4.17. A condition connector and compound transitions

Switch Connector

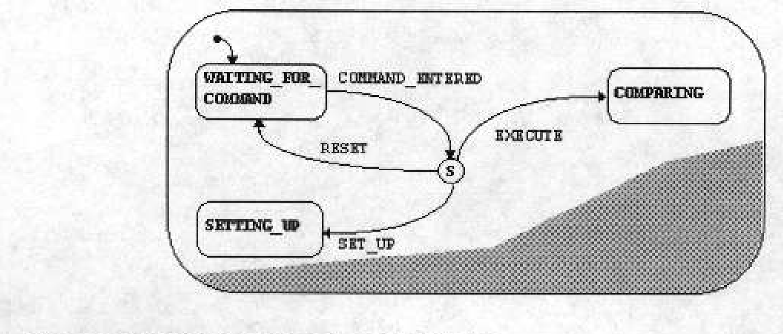
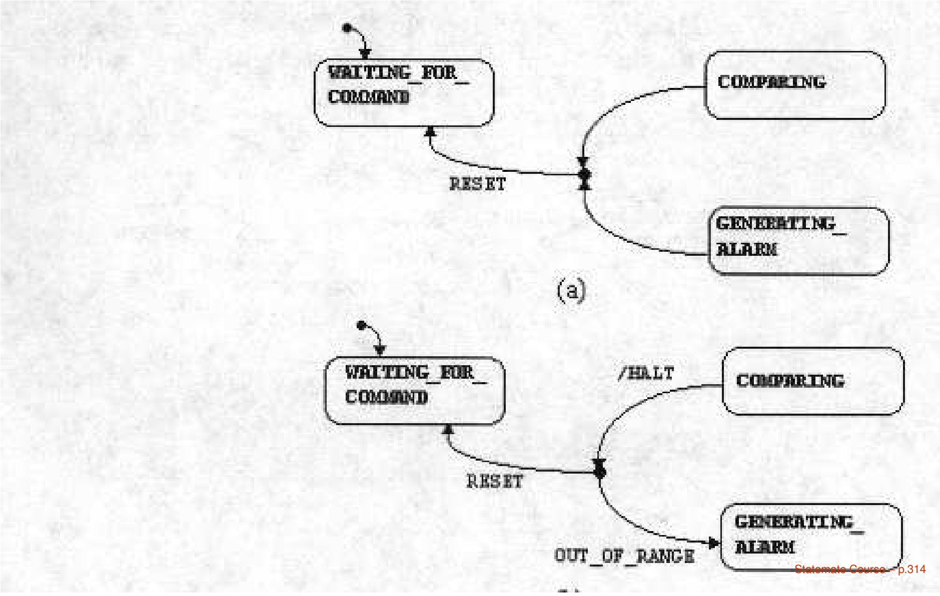


Figure 4.18. A switch connector

Junction Connector



Example

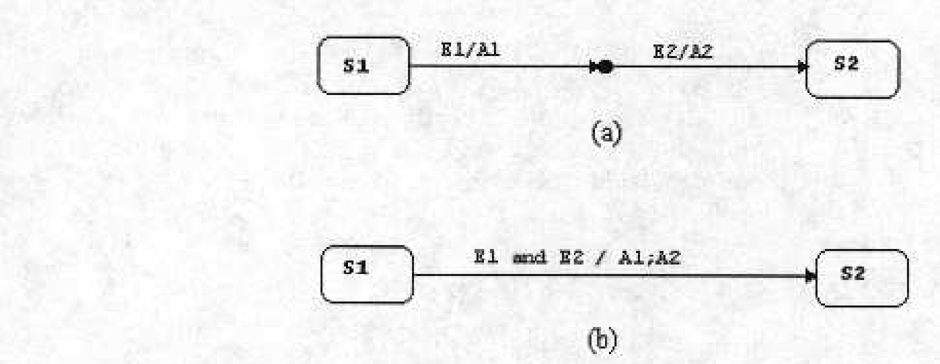


Figure 4.20. Two equivalent transition constructs

Diagram Connector

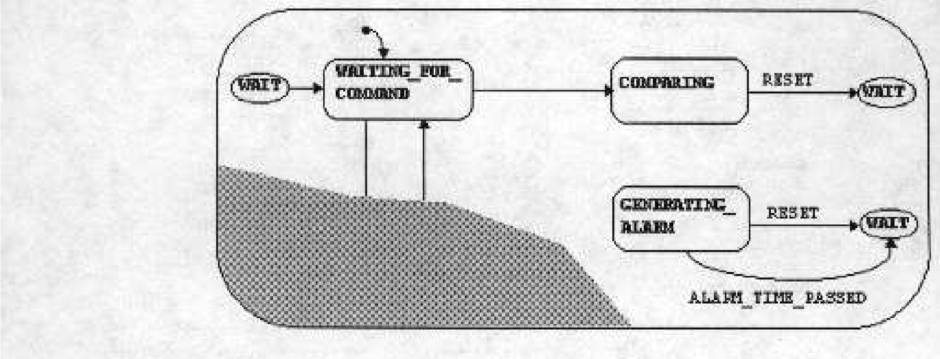


Figure 4.21. Diagram connectors

Transitions to and from And-States

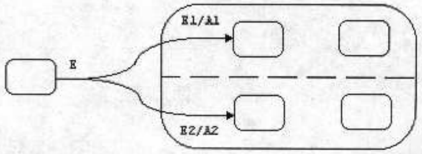


Figure 4.23. Triggers and actions on a fork construct

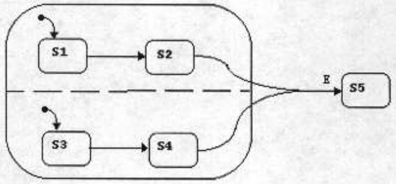


Figure 4.24. A joint connector in a merge construct

Asymmetric Cases

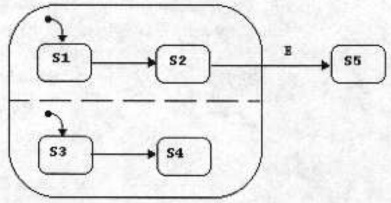
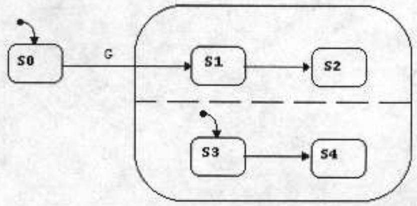


Figure 4.25. A transition from an and-state



Module-Charts

Structural Description: High-Level Design

Module-charts describe the structural view – sometimes called the architectural view – of the system under development. Module-charts are typically used in the high-level design stage of the project.

Structural View

The structural view captures the system's high-level design. A structural description of the system specifies the components that implement the capabilities described by the functional and behavioral views.
These components may be:

- hardware,
- software,
- or even humans.

EWS Example

CCU (control and computation unit): The central CPU, within which the main control of the system and the basic computations take place.

SIGNAL_PROCESSOR: The subsystem that processes the signal produced by the sensor and computes the value to be checked. It consists of an analog-to-digital unit, and a high speed processor that works at the required checking rate.

MONITOR: The subsystem that communicates with the operator. It consists of a **KEYBOARD** for commands and data entry, and a **SCREEN** for displaying messages.

ALARM_SYSTEM: The subsystem that produces the alarm, in visual and/or audible fashion.

PRINTER: The subsystem that receives the messages (text and formatting instructions) and prints them.

Connections to functional view

Sometimes There is a clear correspondence between the top-level activities in the functional view and the top-level subsystems in the structural view, e.g., SIGNAL_PROCESSOR implements the activity PROCESS_SIGNAL.
In other cases the structural decomposition is quite different from the functional decomposition. E.g., the CCU subsystem carries out both the EWS_CONTROL and COMPARE activities, whereas the DISPLAY_FAULT activity is divided into subactivities that are distributed among the ALARM_SYSTEM and MONITOR subsystems.

Internal and External Modules

The structural view is represented by the language of Module-charts.

- There exist two types of **internal** modules:
  - **execution modules**
  - **storage modules**
- And there exist **external modules**

Modules

- Execution modules may be submodules of other external modules only.
- Storage modules may be submodules of other storage modules or of execution modules.
- External modules are always external to an execution module or storage module, and there is no hierarchy of external modules.

EWS-Example

The next figure shows the structural decomposition of the EWS, including a storage module DISK, that stores the fault messages:

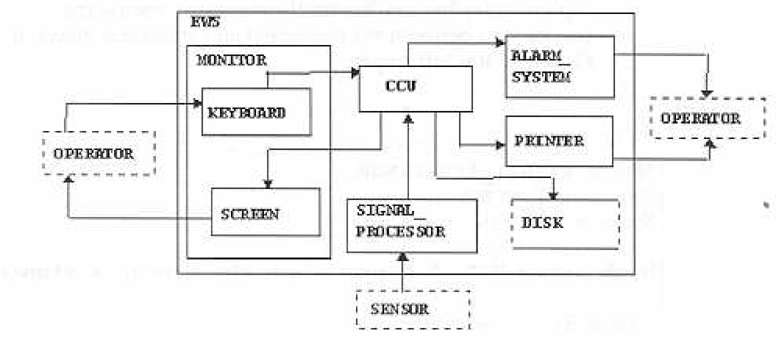
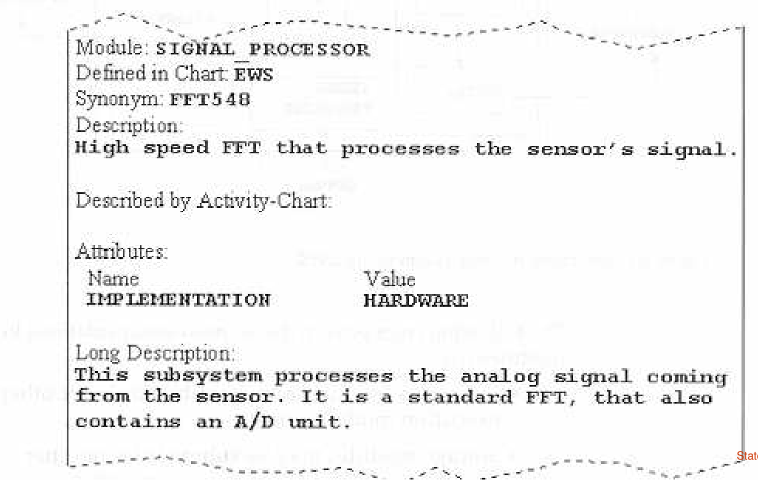


Figure 9.1. Structural decomposition of the EWS

Data Dictionary Entry

The Data Dictionary contains a special field, DESCRIBED BY ACTIVITY-CHART, which is used to connect modules with their functional description:



Module: SIGNAL_PROCESSOR
Defined in Chart: EWS
Synonym: FFT548
Description:
High speed FFT that processes the sensor's signal.

Described by Activity-Chart:

Attributes:

Name	Value
IMPLEMENTATION	HARDWARE

Long Description:
This subsystem processes the analog signal coming from the sensor. It is a standard FFT, that also contains an A/D unit.

Communication Between Modules

As in Activity-charts we use labeled arrows between modules to denote communication between them. They are called **flow-lines** or **m-flow-lines** to emphasize that they connect modules.

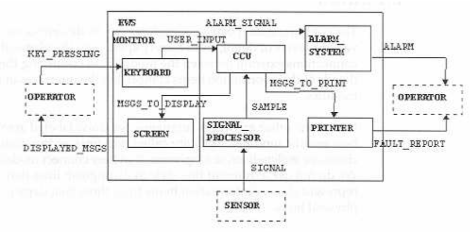


Figure 9.3. Flow of information among modules

Here, USER_INPUT contains the information-flow COMMANDS, the data-item RANGE_LIMITS and the condition SENSOR_CONNECTED.

Physical Links Between Modules

Arrows in a module-chart may also denote physical communication links, or channels, between modules:

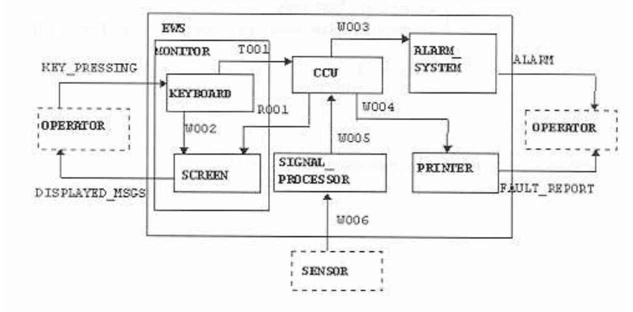
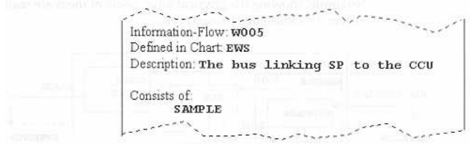


Figure 9.4. Physical links among modules


Information-Flow: W005
Defined in Chart: EWS
Description: The bus linking SP to the CCU

Consists of:
SAMPLE

Connectors and Compound Flow-Lines

Connectors and compound flow-lines are allowed in module-charts exactly as in activity-charts:

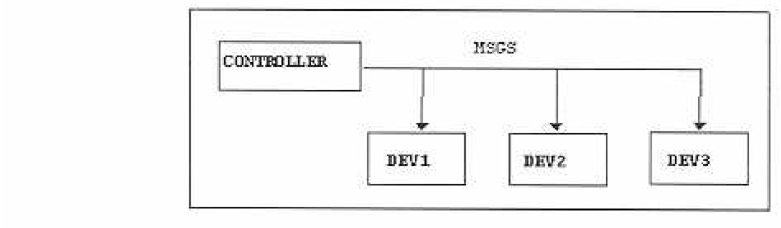


Figure 9.6. Communication link to several devices

Connections Between the Functional and Structural

- The functional view provides a decomposition of the system under development into its functional components, i.e., its capabilities and processes.
- The structural view provides a decomposition of the system into the actual subsystems that will be part of the final system, and which implement its functionality.

Types of connections

There are three types of connections between the functional and structural views:

1. describe the functionality of a module by an activity-chart: **Activity-chart Describing a Module**
2. allocate specific activities in an activity-chart to be implemented in a module: **Activities Implemented by Modules**
3. map activities in the functional description of one module to activities in that of some other module: **Activities Associated with a Module's Activ ities**

Conclusion

In conclusion, we may wish to attach functional descriptions, i.e., activity-charts, to modules on different levels of the structural decomposition:

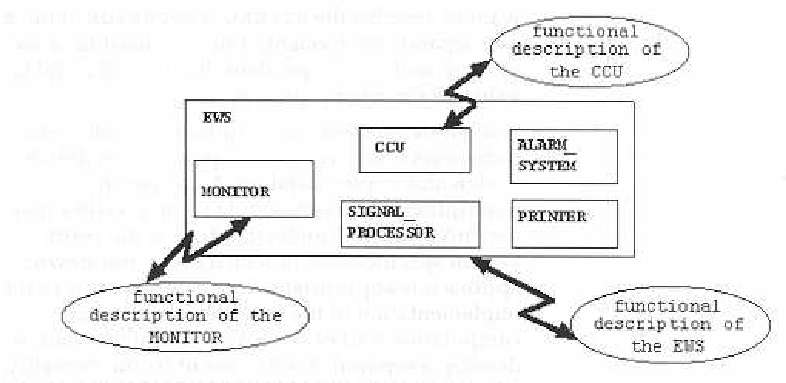


Figure 10.1. Functional descriptions attached to different modules

Activity-chart Describing a Module

The activity-chart EWS_ACTIVITIES

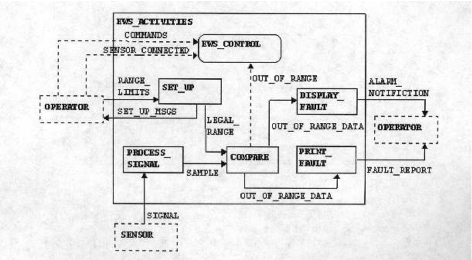
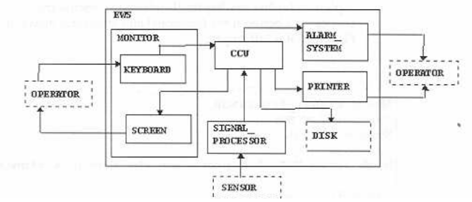


Figure 2.5. EWS_ACTIVITIES, its environment and flow of information

describes the functionality of the module EWS



This connection is specified in the Data Dictionary:

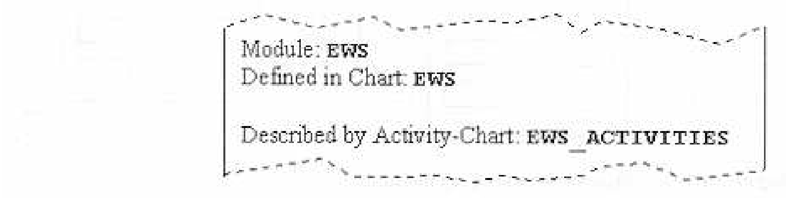


Figure 10.2. A module described by activity-chart

Notice that the connection is between an activity-chart and a module!

Top-Down Approach

One may now want to specify an activity-chart CCU_AC for the module CCU:

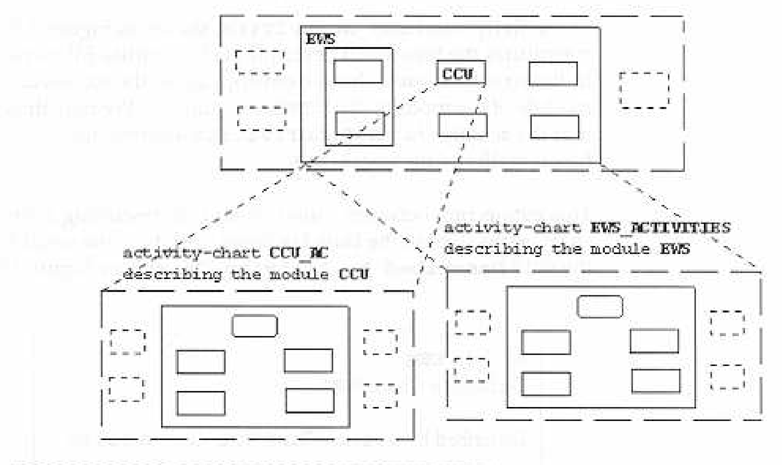
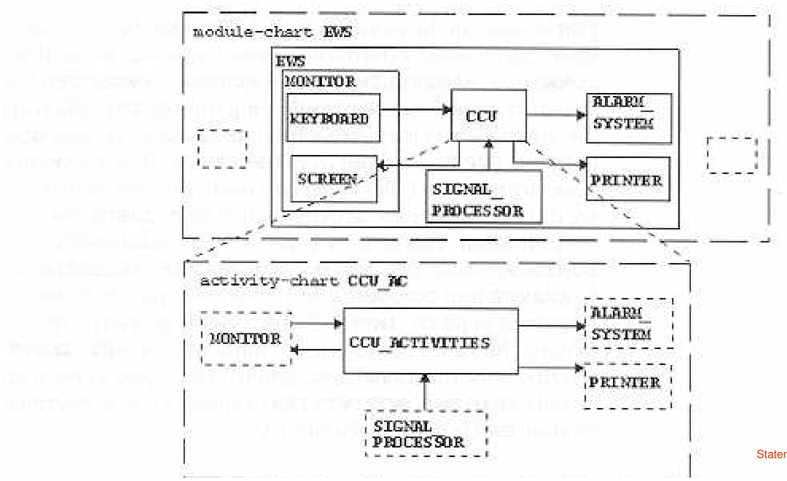


Figure 10.3. Activity-charts describing modules

Correspondence between views

There must be a correspondence between the functional and structural decompositions of a module in terms of the environment and the interface with it:



Since also the flow-lines have to be correct we have to introduce an activity GET_INPUT which will be implemented by the MONITOR module:

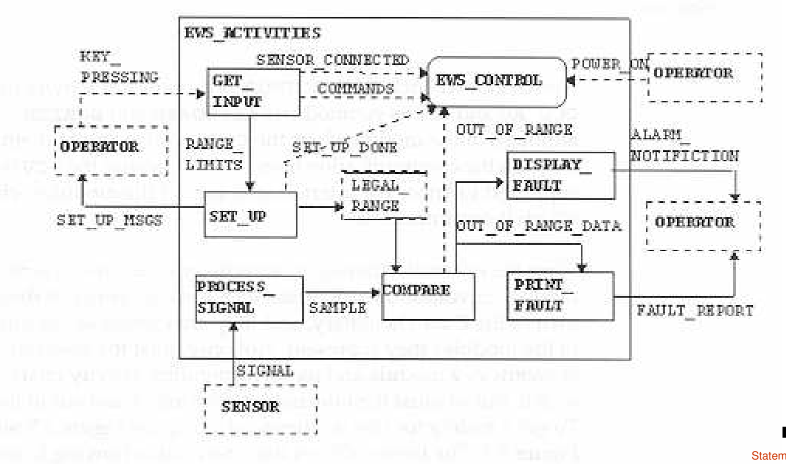


Figure 10.5. Revised activity-chart describing the

Activities implemented by Modules

When the module described by the activity-chart is eventually decomposed into submodules, we may be more concrete and allocate the relevant activities and data-stores to the submodules:

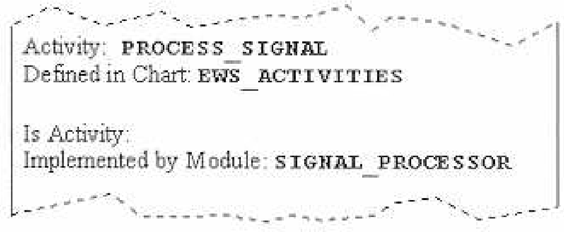
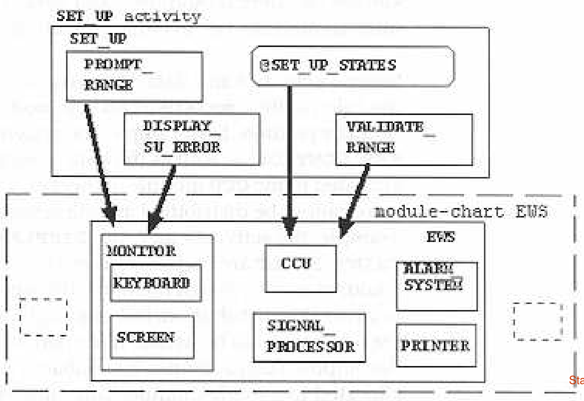


Figure 10.6. An activity implemented by a module

A single activity or data-store cannot be distributed among several modules.
Therefore, one has to decompose such activities (or data-stores) into subactivities that can each be allocated to a single module:



Activities Associated with a Module's Activities

On the one hand, there is the EWS_ACTIVITIES describing the functionality of the whole system. On the other hand, also the submodules implement activities:

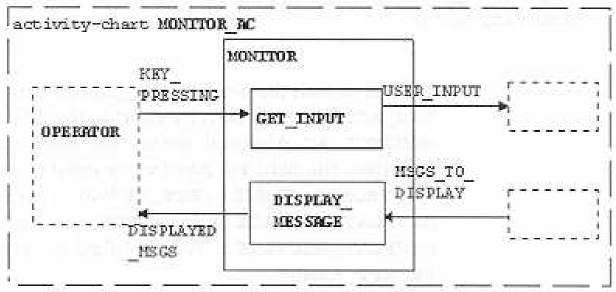


Figure 10.8. Activity-chart of MONITOR

Then, one wishes to associate subactivities of EWS_ACTIVITIES with those implemented by a submodule:

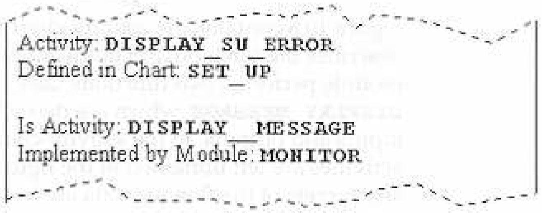


Figure 10.9. Mapping of activities by the is activity relation

Communication between Activities and Module-Char

We discuss the mechanismens used to communicate bewteen actions.
As last language in STATEMATE we introduce Module-Charts. Module-charts describe the structural view – sometimes called the architectural view – of the system under development.
Module-charts are typically used in the high-level design stage of the project.

[HP98] Modeling Reactive Systems with Statecharts: The STATEMATE Approach, D. Harel, M, Politi. McGraw-Hill, 1998.

Communication between Activities

Specifying the communication between activities consists of the what and the when, just like for other parts of the specification.
The what is described by the flow-lines in the activity-charts and relevant parts of the Data Dictionary. The when is to be specified by the behavioral parts of the model, i.e., the statecharts and mini-specs.

Communication and Synchronization Issues

Functional components in systems communicate between themselves in order to pass along information and to help synchronize their processing. A number of attributes characterize the various communication mechanisms.

Attributes

Communication can be

- **instantaneous** , meaning that it is lost when not consumed immediately, or
  persistent , meaning that it stays around until it gets consumed.
- **synchronous** , i.e., the sender waits for an acknowledgment, or
  asynchronous , i.e., there is no waiting on the part of the sender
- **directly addressed** , i.e., the target is specified, or sent by
  broadcasting

Controlling the Flow of Information

In the following figure X is specified to flow between activities A and B:

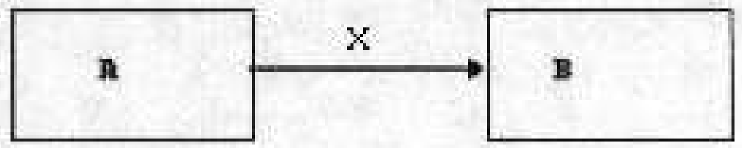


Figure 8.1. An information element flowing between activities

Flow of Information

If x is an event we may have the following situation:

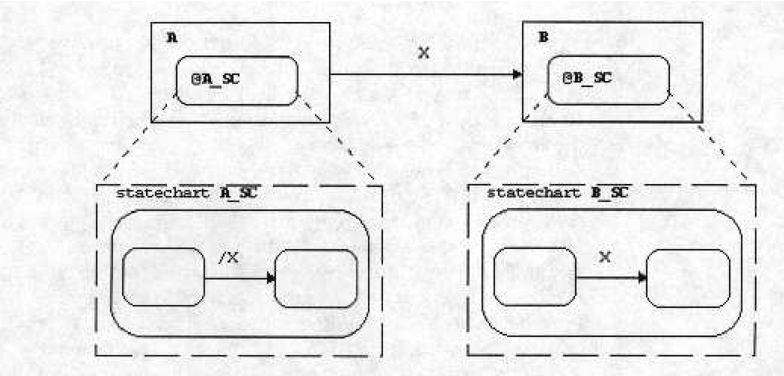


Figure 8.2. Producing and consuming an event

If x is a condition or data-item modified by A, B could sense the value or the change of the value (x, TR(x), WR(x)).

Examples of Communication Control

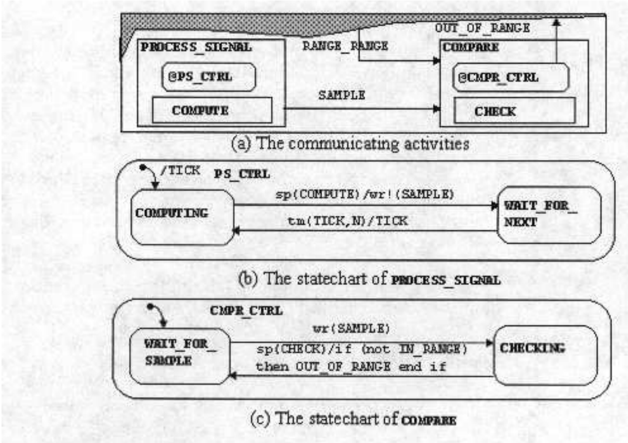


Figure 8.4. Communication between periodic activities

Message Passing

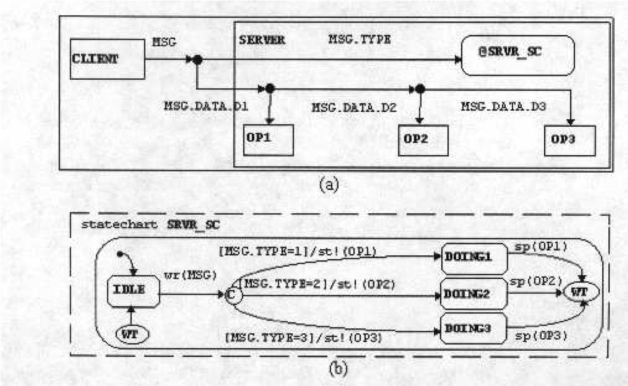


Figure 8.5. Server responding to three service requests

Activities Communicating Through Queues

Queuing facilities for messages are virtually indispensable in modeling multi-processing environments, and especially multiple client-server systems.
We want to have:

- ability to sent unlimited number of messages to the same address, while the receiver is not always in a position to accept them,
- no message is consumed before one that was sent earlier,
- possibility for concurrently active components to write messages to the same address at the same moment
- possibility for concurrently active components to read different messages to the same address at the same moment

Queues and their operations

A queue is an ordered, unlimited collection of data-items, all of the same data type. The queue is usually shared among several activities, which can employ special actions to add elements to the queue and read and remove elements from it.

- **q_put(Q,D)** add the value of expression D to the queue
- **q_urgent_put(Q,D)** add the value of expression D to the head of the queue
- **q_get(Q,D,S)** extract the element at the head of Q and place it in D
- **q_peek(Q,D,S)** same as above without removing the element from Q
- **q_flush(Q)** clears Q totally

Combination with Data Stores

The following figure illustrates the order in which operations on a queue are performed during a step:

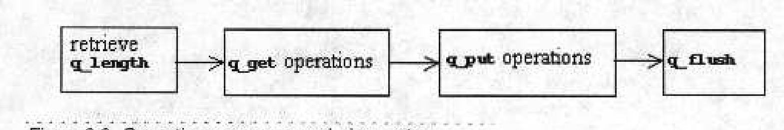


Figure 8.6. Operations on a queue during a step

Queues can be associated with data stores just like data-items of other types can.

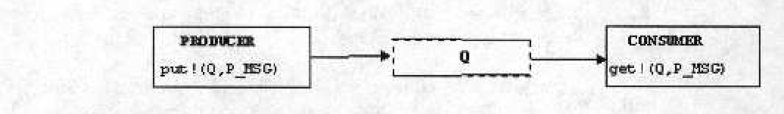


Figure 8.7. A queue associated with a data-store

Example

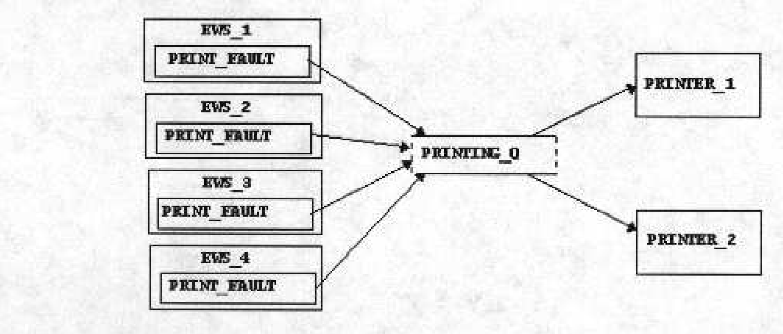


Figure 8.8. Multiple clients served by multiple servers via a queue

Example

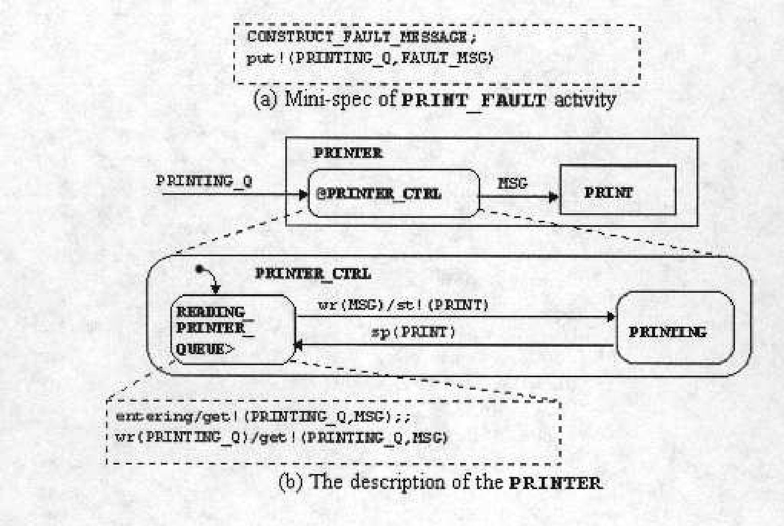


Figure 8.9. Writing and reading messages from a queue

Conditions and Events Related to States

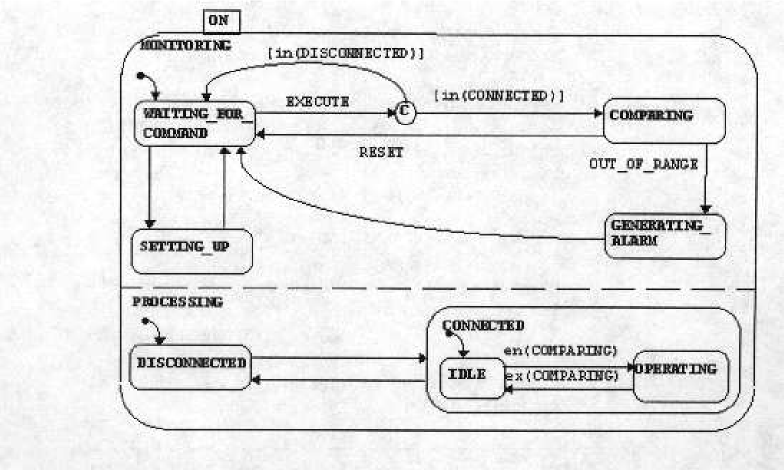


Figure 4.15. Conditions and events related to states

Condition Connector

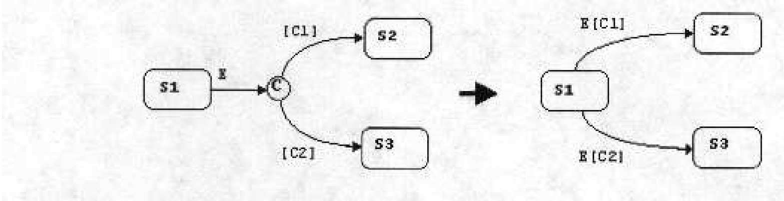


Figure 4.17. A condition connector and compound transitions

Switch Connector

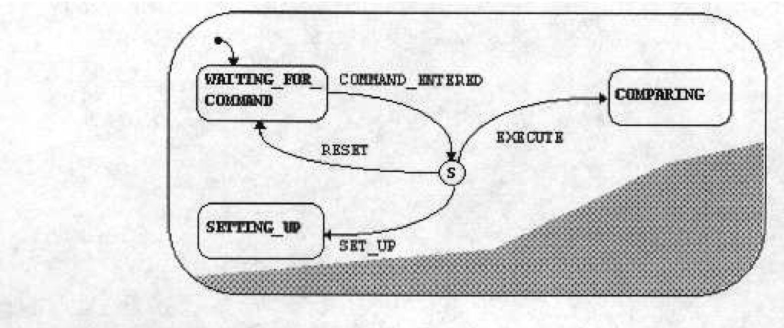
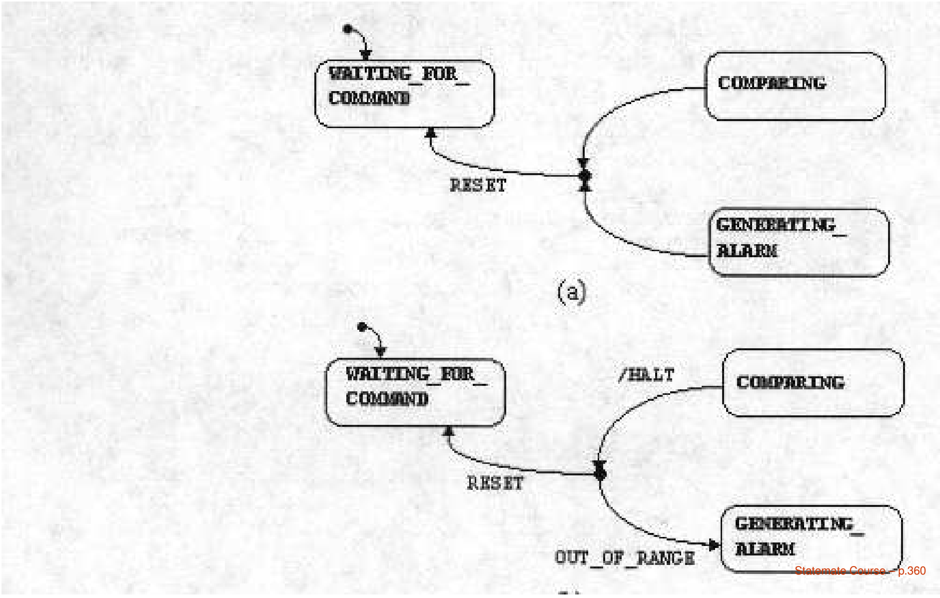


Figure 4.18. A switch connector

Junction Connector



Example

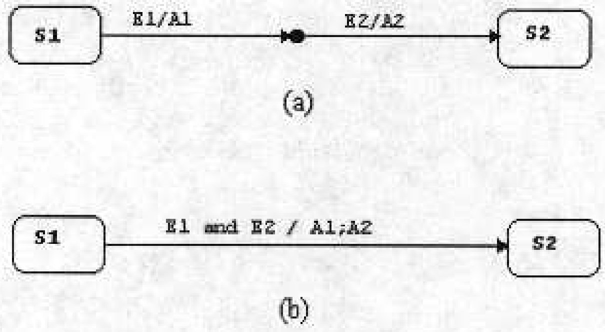


Figure 4.20. Two equivalent transition constructs

Diagram Connector

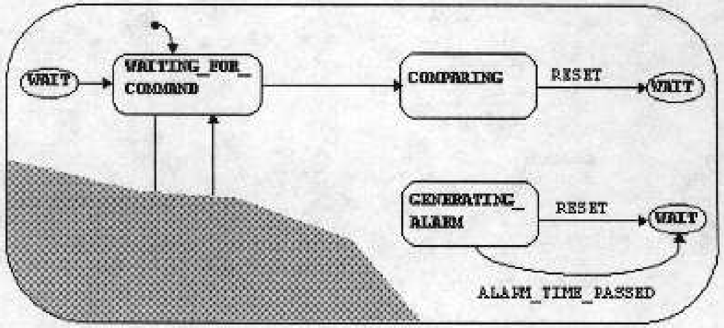


Figure 4.21. Diagram connectors

Transitions to and from And-States

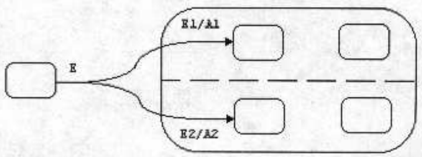


Figure 4.23. Triggers and actions on a fork construct

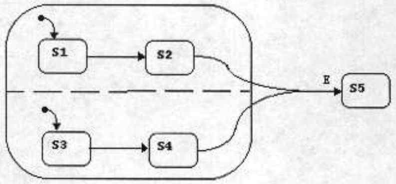


Figure 4.24. A joint connector in a merge construct

Asymmetric Cases

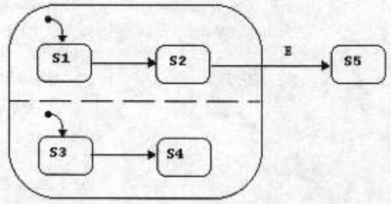
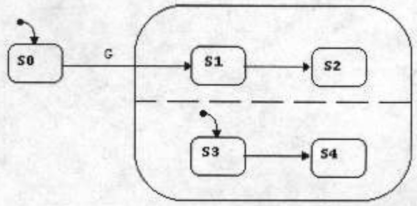


Figure 4.25. A transition from an and-state



Module-Charts

Structural Description: High-Level Design

Module-charts describe the structural view – sometimes called the architectural view – of the system under development. Module-charts are typically used in the high-level design stage of the project.

Structural View

The structural view captures the system's high-level design. A structural description of the system specifies the components that implement the capabilities described by the functional and behavioral views.
These components may be:

- hardware,
- software,
- or even humans.

EWS Example

CCU (control and computation unit): The central CPU, within which the main control of the system and the basic computations take place.

SIGNAL_PROCESSOR: The subsystem that processes the signal produced by the sensor and computes the value to be checked. It consists of an analog-to-digital unit, and a high speed processor that works at the required checking rate.

MONITOR: The subsystem that communicates with the operator. It consists of a KEYBOARD for commands and data entry, and a SCREEN for displaying messages.

ALARM_SYSTEM: The subsystem that produces the alarm, in visual and/or audible fashion.

PRINTER: The subsystem that receives the messages (text and formatting instructions) and prints them.

Connections to functional view

Sometimes There is a clear correspondence between the top-level activities in the functional view and the top-level subsystems in the structural view, e.g., SIGNAL_PROCESSOR implements the activity PROCESS_SIGNAL.
In other cases the structural decomposition is quite different from the functional decomposition. E.g., the CCU subsystem carries out both the EWS_CONTROL and COMPARE activities, whereas the DISPLAY_FAULT activity is divided into subactivities that are distributed among the ALARM_SYSTEM and MONITOR subsystems.

Internal and External Modules

The structural view is represented by the language of Module-charts.

- There exist two types of **internal** modules:
  - **execution modules**
  - **storage modules**
- And there exist **external modules**

Modules

- Execution modules may be submodules of other external modules only.
- Storage modules may be submodules of other storage modules or of execution modules.
- External modules are always external to an execution module or storage module, and there is no hierarchy of external modules.

EWS-Example

The next figure shows the structural decomposition of the EWS, including a storage module DISK, that stores the fault messages:

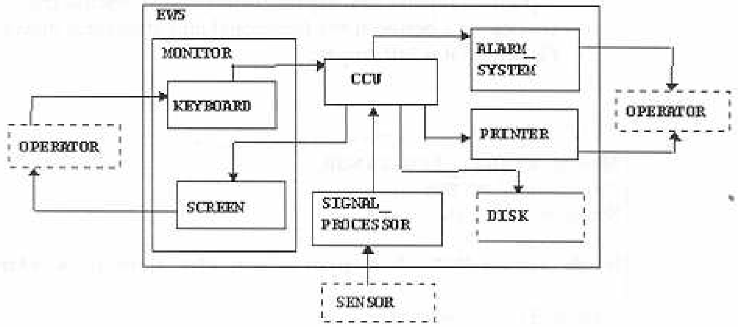


Figure 9.1. Structural decomposition of the EWS

Data Dictionary Entry

The Data Dictionary contains a special field, DESCRIBED BY ACTIVITY-CHART, which is used to connect modules with their functional description:

Module: `SIGNAL_PROCESSOR`
Defined in Chart: `EWS`
Synonym: `FFT548`
Description:
`High speed FFT that processes the sensor's signal.`

Described by Activity-Chart:

Attributes:

Name	Value
`IMPLEMENTATION`	`HARDWARE`

Long Description:
`This subsystem processes the analog signal coming from the sensor. It is a standard FFT, that also contains an A/D unit.`

Communication Between Modules

As in Activity-charts we use labeled arrows between modules to denote communication between them. They are called **flow-lines** or **m-flow-lines** to emphasize that they connect modules.

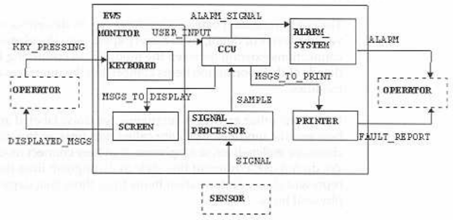


Figure 9.3. Flow of information among modules

Here, USER_INPUT contains the information-flow COMMANDS, the data-item RANGE_LIMITS and the condition SENSOR_CONNECTED.

Physical Links Between Modules

Arrows in a module-chart may also denote physical communication links, or channels, between modules:

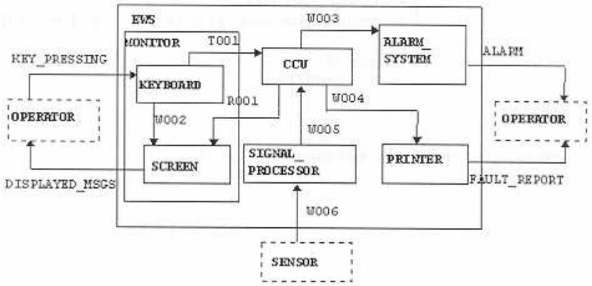


Figure 9.4. Physical links among modules

Information-Flow: `W005`
Defined in Chart: `EWS`
Description: `The bus linking SP to the CCU`

Consists of:
`SAMPLE`

Connectors and Compound Flow-Lines

Connectors and compound flow-lines are allowed in module-charts exactly as in activity-charts:

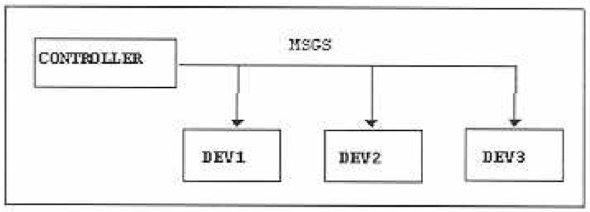


Figure 9.6. Communication link to several devices

Connections Between the Functional and Structural

- The functional view provides a decomposition of the system under development into its functional components, i.e., its capabilities and processes.
- The structural view provides a decomposition of the system into the actual subsystems that will be part of the final system, and which implement its functionality.

Types of connections

There are three types of connections between the functional and structural views:

1. describe the functionality of a module by an activity-chart: **Activity-chart Describing a Module**
2. allocate specific activities in an activity-chart to be implemented in a module: **Activities Implemented by Modules**
3. map activities in the functional description of one module to activities in that of some other module: **Activities Associated with a Module's Activ ities**

Conclusion

In conclusion, we may wish to attach functional descriptions, i.e., activity-charts, to modules on different levels of the structural decomposition:

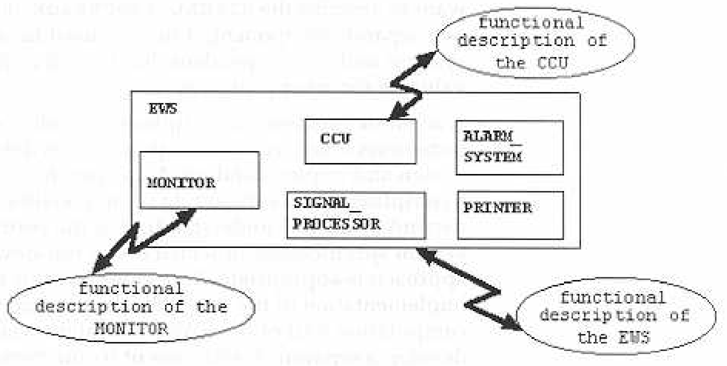
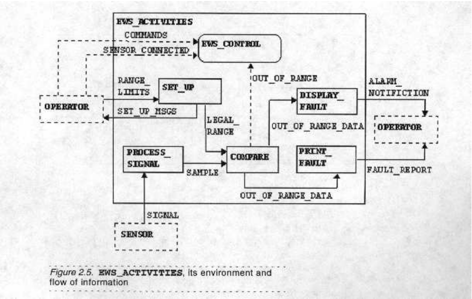


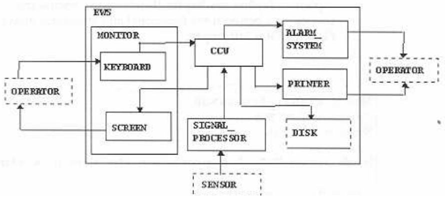
Figure 10.1. Functional descriptions attached to different modules

Activity-chart Describing a Module

The activity-chart EWS_ACTIVITIES



describes the functionality of the module EWS



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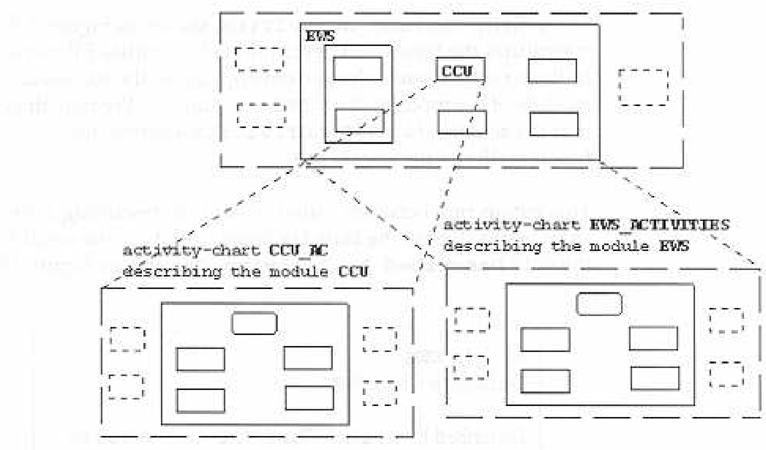

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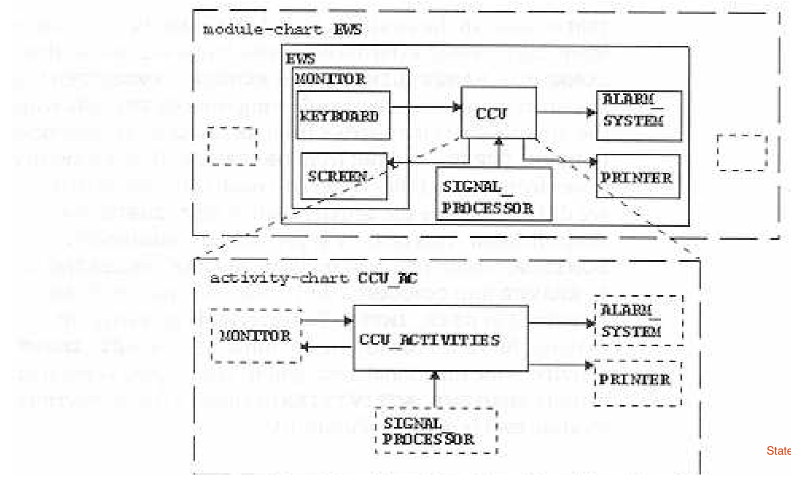

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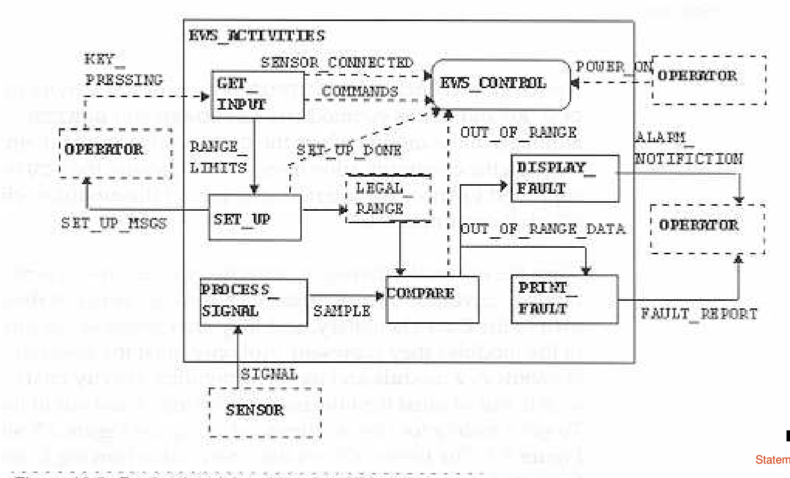

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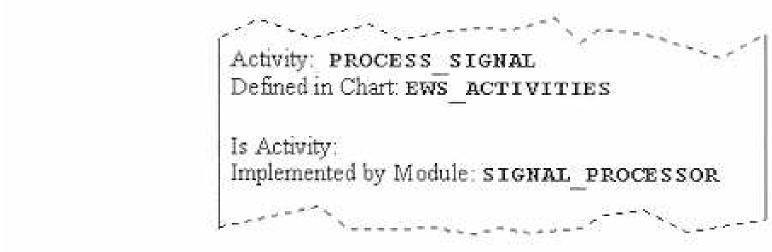

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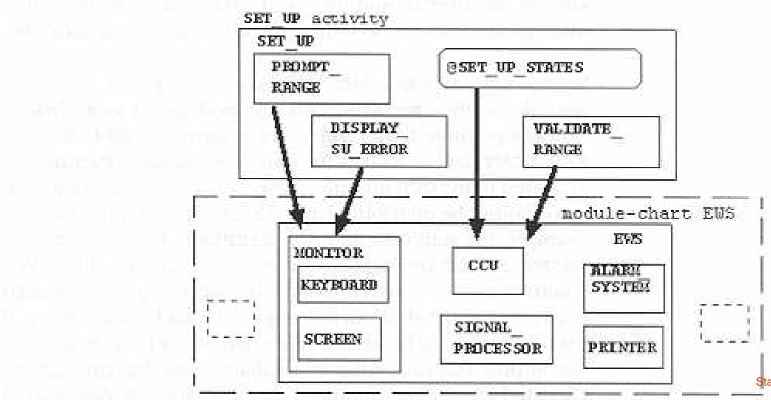

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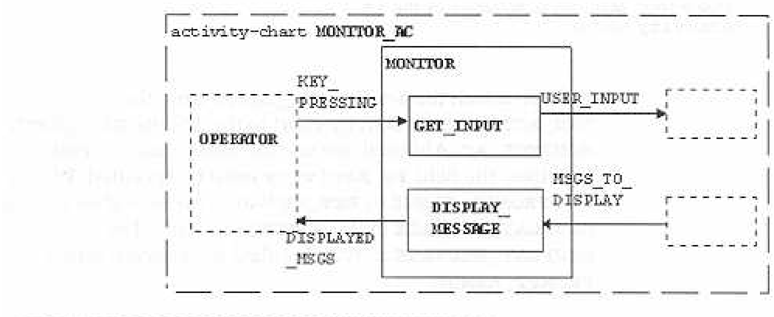

Figure 10.8. Activity-chart of MONITOR

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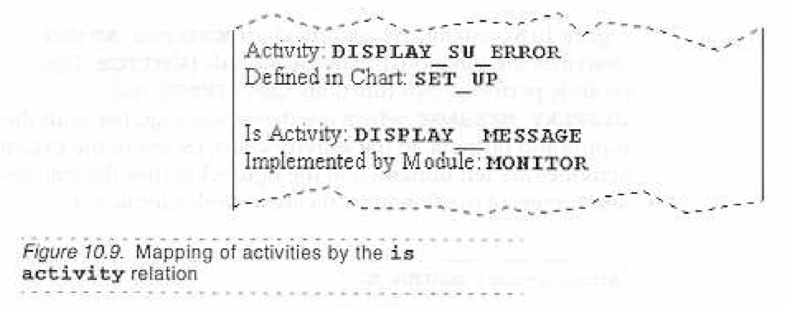
Activity: DISPLAY_SU_ERROR
Defined in Chart: SET_UP

Is Activity: DISPLAY_MESSAGE
Implemented by Module: MONITOR

Figure 10.9. Mapping of activities by the **is activity** relation