PART IV

Planning with Time and Resources

This part of the book is devoted to planning with time and resources. We will be relaxing assumption A6 (Section 1.5), i.e., we will make time explicit in the representation. However, we will keep assuming a deterministic system with complete knowledge and no uncertainty (these three assumptions will be relaxed in Part V). Part IV includes three chapters, on temporal reasoning, temporal planning, and resource handling. In this introduction, we motivate the need for explicit time and give an overview of the representation and approaches detailed in Chapters 13, 14, and 15.

The conceptual model for planning described in Section 1.4 is mainly a general model for a dynamic system. Up to here we relied on the model of state-transition systems with the restrictive assumption of implicit time (assumption A6). In this model the dynamics are represented as a sequence of states; actions and events are instantaneous state transitions; the planning goals are not constrained in time. This restricted model is quite useful for studying the logics and computational aspects of planning with simple state-transition operators. However, in many applications, it is not realistic.

In reality, actions do occur over a time span. A finer model of an action should account not only for the preconditions *before* the action starts but also for other conditions that should prevail *while* it is taking place. Such a model should represent the effects of an action throughout its duration and the delayed effects after the action has finished. For example, consider the move action in the DWR domain, which requires free space for the robot at its destination. In the real domain, this condition is needed not when the action starts but only when the robot reaches its destination. The effect of allowing free space in the origin location does not take place when the action ends but as soon as the robot leaves. Actions may overlap even if their conditions and effects are not independent.[1] In such a case, concurrency of actions is more realistically handled with an explicit time representation.

Furthermore, often goals in a plan are meaningful only if achieved within a time bound. In a dynamic environment, various events may be expected to occur at future time periods. Hence, actions have to be located in time with respect to expected events and to goals. Time is required in two forms: (1) *qualitatively*, to handle synchronization between actions and with events, e.g., to plan for a robot to move to a destination that is not yet free; and (2) *quantitatively*, as a resource, to model the duration of actions with respect to deadlines or cost functions, e.g., to plan how to load or unload all the containers of a ship before its departure.

The main reasons for making time explicit in planning can be summarized as the following list of actions one can perform.

- Model the durations of actions, e.g., to treat time as a resource.
- Model the effects and conditions of an action at various points along its duration, including delayed effects.
- Handle goals with relative or absolute temporal constraints.
- Take into account the dynamics of a domain, i.e., events expected to occur at some future time that are not the results of planned actions.
- Plan with actions that *maintain* a value while being executed, as opposed to just changing that value, e.g., tracking a moving target or keeping a spring latch compressed.
- Plan with overlapping actions that have *interacting* and *joint effects*. For example, a door that has a knob and a spring latch that controls the knob requires two actions to be opened: (1) pushing and maintaining the latch *while* (2) turning the knob.

An explicit representation of time can significantly extend the expressiveness of the planning model. One may pursue such an extension in either of the following two ways.

1. Keep the notion of global states of the world and include time explicitly in the representation of state-transition systems, e.g., as in timed automata. This approach will not be developed here. This state-oriented view models the dynamics of the world as a sequence of global states or snapshots of the entire domain.
2. Take another view that deals not with a set of states but with a set of functions of time describing parallel evolutions. This time-oriented view represents the dynamics of the world as a collection of partial functions of time describing local evolutions of a state variable.

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1. In classical planning, only independent actions, as defined in Chapters 5 and 6, are allowed to overlap.

These two views are represented in Figure IV.1, where time is the horizontal axis and state variables are along the vertical axis. In the state-oriented view, the elementary component is a state, i.e., a "vertical slice" or snapshot that gives a complete description of the domain at a single time point. In the time-oriented view, the building block is a function of time, i.e., a "horizontal slice" that focuses on just one state variable and gives its evolution along the time line.

Example IV.1 The state-oriented view, on which we relied up to now, is illustrated in Figure 1.1 for the DWR domain as a set of six states. One possible *trajectory* for this dynamic system is, e.g., the sequence of states $\langle s_0, s_2, s_3, s_4 \rangle$. In the time-oriented view, the same trajectory can be described, informally and qualitatively, as three concurrent functions of time for three variables describing, respectively, the behavior of the robot, the crane, and the container.

- The robot moves from location 1 to location 2 unloaded, then it gets loaded with the container, then it moves to location 2.
- The crane picks up the container and puts it on the robot when the robot is at location 1.
- The container is on top of the pallet in location 1, then it gets loaded onto the robot at that location and gets moved to location 2.

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This part of the book introduces a shift of focus. We will be moving from the state-oriented view to the time-oriented view. Although there are some approaches to temporal planning that rely on timed extensions of state-transition systems (e.g., [24, 374, 376]), most approaches adopt the time-oriented view that appears more natural and conceptually simpler.

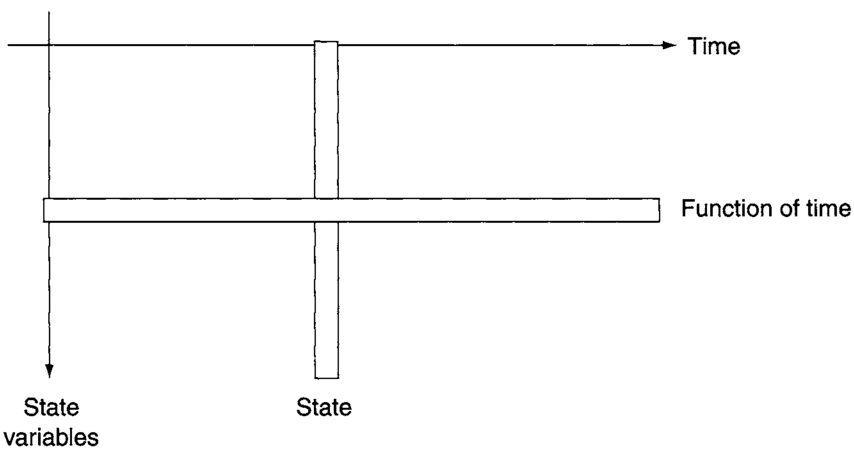

Figure IV.1 From a state-oriented to a time-oriented view of the dynamics.

An appealing advantage of this time-oriented view is that it makes use of well-developed representations of time and temporal reasoning techniques. Chapter 13 is entirely devoted to these techniques. Temporal planning is addressed in Chapter 14.

Another good reason for adopting the time-oriented view is its closeness to scheduling techniques. This makes it possible to integrate the synthesis of plans to the scheduling of actions and resource allocation. Chapter 15 is devoted to planning and resource scheduling.