imply that the final design is the reference point for the design process. From the point of view of designing, the important reference point is the current understanding of the design, which is distributed among the members of the design team, and the activities that the designers need to undertake in order to advance the design towards the design requirements (recognizing that the evolution of these requirements is also part of the process of designing). Seen from this point of view, the notion of the "final design" seems relatively inconsequential. It could also be argued that designs are never finished. Hence, I decided that there was no need for a scale to compare the current state of the design with the "finished design." The abstract-concrete scale would suffice to represent issues that relate to the flexibility and directness of interpretation. The two key points about the abstract-concrete scale are that a) abstract representations offer more flexibility in interpretation than concrete ones, and b) different representations convey different kinds of information more directly than others. The suitability of any given representation to a task depends on the information sought by the designer.

Material representations

In this chapter I am concerned with material representations – pieces of hardware – and the way in which they are used in designing. Material representations are external representations. They are specific concrete physical representations. Because they can be reconfigured, they vary on the scale from transient to durable and self-generated to ready-made. The ability to reconfigure and reinterpret material representations is where their power lies in helping designers to think and learn. This chapter illustrates the way that material representations are challenged against abstract representations, such as design requirements, in order to advance the design. It illustrates the way that theoretical predictions derived from abstract fundamental concepts, such as Newton's laws, are challenged against the behaviour of physical devices in order to refine the theoretical model and further the student's understanding of engineering fundamentals. The latter is dealt with more thoroughly in Brereton 1998.

Hardware

I use the term "hardware" as shorthand to refer to material representations in general. The term covers raw materials such as string, cardboard, wood, and steel, as well as physical devices that have been fashioned from raw materials. (I regard sketches as abstract representations drawn on a piece of physical material, not material representations in and of themselves.) I use the term "physical device" when I am referring specifically to pieces of machinery and not to raw materials.

Data Gathering

Several engineering design activities were videotaped and analyzed in order to determine the roles played by hardware in supporting group activity and the resulting contributions to design thinking (see Figure 4.2). For a full description of these activities and the larger study from which this chapter is derived, see Brereton (1998). The activities varied from a concept sketching exercise in which no hardware was available to projects in which a kit of hardware was provided and augmented with other hardware as the designers saw fit. The activities were:

1. a conceptual design session in which groups of students sketched ideas for a kitchen scale mechanism (no hardware);
2. a design and build exercise in which kit hardware was used to build an aluminum crane (kit hardware);
3. a design project in which a group of students designed an energy efficient model All Terrain Vehicle using a Lego kit, a choice of motors and other hardware (kit hardware and evolving project hardware).

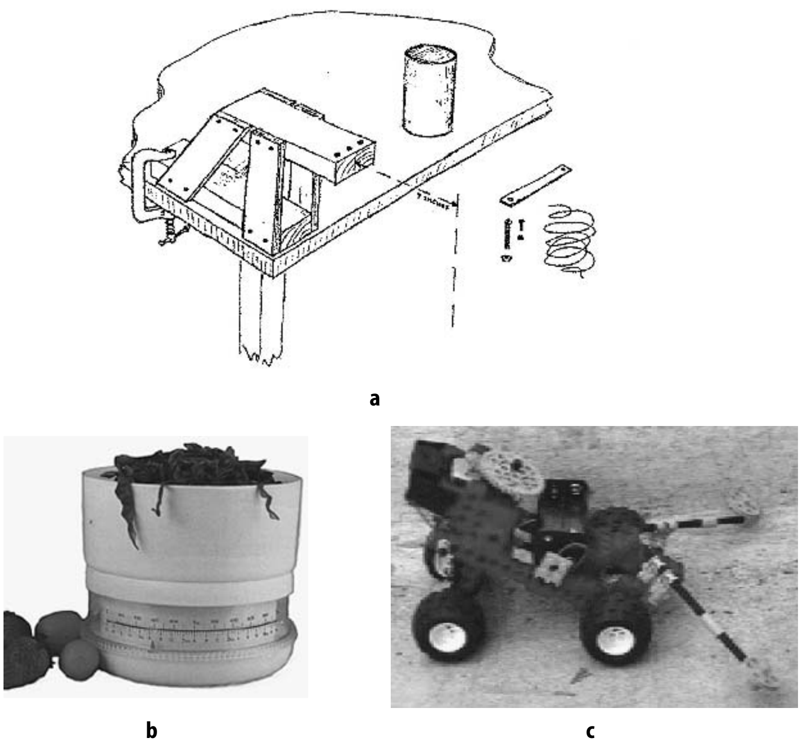

Figure 4.2 Design activities that formed the subject of this study.
a Crane design. Design a structure to support a 20lb load 9in out from the end of the platform using a kit of hardware that included aluminium strips, nuts and bolds, screws and string. Duration: 90 minutes. Exercise and sketch from Miller (1995).
b Kitchen scales mechanism conceptual design. Design an internal mechanism for the scale concept shown above. The mechanism should transfer the weight from the scale pan into the rotation of a pointer in the horizontal plane. Exercise duration: 30 minutes.
c Energy efficient all-terrain vehicle project. Design an efficient model all-terrain vehicle using Lego, and batteries and motor of your choice. This vehicle must cross a stretch of gravel and climb a carpeted ramp using as little energy as possible. Energy consumed during performance trials will be measured by instrumenting the vehicle to determine the average current and voltage levels. Project duration: two and a half weeks.