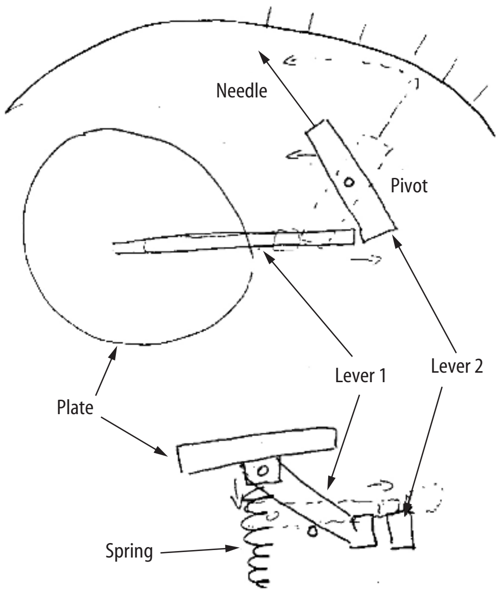

Left: Student's concept sketch of a kitchen scale designed by gesturing with pens.
Below: Transcript of a student describing his group's design to the class. While describing the design, the student gestures with pens and points at the sketch. Typed labels and arrows are added for clarity by the author.

"I was working on the kitchen sacle design.

Ther's a spring there and there's a plate pushing down on top, OK? And that's pushing down this lever which, as that is pushed down on [the top] end, this [lower end] is moved out.

And that movement in that direction is pushing the base of another lever here which is pivoted over here. So, as that moves out, that moves the needle around. So it's a really simple design."

Figure 4.7 Hardware as thinking prop – students appropriate convenient hardware to think and experiment with.

longer projects. It lends support to the idea that an accurate model is less important than a quick model that helps to explore the space.

Figure 4.7 shows a design that was developed by a group who gestured with pens in their hands to develop a linkage mechanism. The pens formed the two levers of the linkage mechanism.

Hardware as a chameleon

Hardware relies on its context of use for its functional meaning. A paper-clip may be seen as:

- a device to hold pieces of paper together;
- a thin piece of wire for picking a lock;
- a thin piece of wire for pressing a recessed button to restart a computer;
- an electrical conductor.

There is a sense in which hardware function is indexical,[1] in that it relies on its context of use for its particular functional meaning. It is analogous to language in the way that its meaning changes with its context of use.[2] Brown et al. (1989) argued that machines indexicalize abstract representations, pointing out that "in an intriguing way you need the machine to understand the manual as much as you need the manual to understand the machine". In fixing my own old car I have found it helped to have several manuals in addition to the car. The car helps me to interpret the manuals and each manual helps to interpret the other manuals.

Abstract representations, such as engineering drawings or theoretical concepts, on the one hand, have conventional meanings which hold on any occasion of their use, but, on the other hand, they draw their meaning from the physical world. They are derived from and understood by the variety of specific physical scenarios to which they apply. In learning to use abstract representations it is thus necessary to understand and discover them in the context of specific physical scenarios.

Hardware as a medium of integration

Integration, the bringing together of different components to synthesize a new whole, distinguishes design from analysis. Integration typically reveals all manner of issues that cannot be anticipated. It is a great source of learning.

When designers integrate components in a design, they learn both about the individual components and the interfacing issues that ensure that one component works properly with the next. Integrating components in their functional context reveals their:

- practical limits of use;
- characteristics of operation;
- methods of connection;
- causal relations;
- independent variables; and
- physical quantities.

This empirical knowledge extends the designer's hardware repertoire[3] (Schön, 1994).

Developing the hardware repertoire through integration

As designers explore ways to meet design requirements, they expand their hardware repertoire. By a "hardware repertoire" I mean a repertoire of components, materials, synthesis skills and associated design contexts with which designers have experience. When designers "add" a component to their design repertoire, they develop the knowledge of its characteristics and the limits of its behaviour in the context of use. They develop this knowledge through attempting to integrate the component into a design, with a design goal in mind. The knowledge that results from this attempt then forms part of the repertoire on which they draw in future design projects.

I will illustrate the notion of learning through integrating components with an example drawn from a two-week project to design an efficient model all-terrain vehicle. This vehicle must cross a stretch of gravel and climb a carpeted ramp using the least amount of energy possible. The design project necessitated that students negotiate between abstract and material representations, as must be done in professional engineering design practice. They had to select motors from data sheets and had to present quantitative experimental results in a design document, as well as build a hardware device. Table 4.2. summarizes a variety of student discoveries that occurred through hardware integration in the all-terrain vehicle project. Many of the discoveries are