resting on, but not secured to the chassis, they were visibly surprised as the motor leapt off the chassis. They had not anticipated that the motor must be secured in order to react to the motor torque through the chassis. Having secured the motor to the chassis and connected it to the wheel axles through a gear train, they switched on power again. This time they noticed that the wheels spun when the vehicle was held in the air, but that the vehicle would not move when placed on the ground. They identified correctly that they needed more torque at the wheels and added another gear stage to the transmission. They pointed out the relative speed of the wheels in the air compared to their speed along hard and carpeted floors. They commented when it stalled in various conditions. They hooked it up to a multimeter to find out how much current it drew from the batteries. When the leads came off and they hooked them back up, they suddenly noticed and remarked that the motor was going in the other direction. They deduced that they had reversed the current direction and then reversed the leads to check that the motor turned the opposite way again. They noted that for this kind of motor, the direction of the current mattered.

Through synthesis and testing the students made several empirical discoveries relating to torque, current, speed and stall, listed in Table 4.2. They got a "feel" for motors, developing an understanding of their characteristics and limits of use. Even though Sean and Carol did not make a connection to the lecture material in the first instance, they gradually did so throughout the course of the exercise. They came to understand that the applied load was the reference variable that controlled motor speed; that too much load leads to stall, etc. They learned about abstract concepts through integrating physical components because successful physical integration demanded that they understood the operational characteristics of components under specific interfacing conditions. Furthermore, the knowledge that they gained is based in a design context – the next time the students encounter stall, they are likely to think of their all-terrain vehicle stalling under different conditions. Having had such experiences and developed empirical knowledge of the motor's performance characteristics and physical limits, the students are developing, one can presume, the kind of experiential knowledge that is associated with experts who have many previous design projects to draw on – that is, they are expanding their hardware repertoire through integrating components.

In summary, students develop a large amount of empirical knowledge in designing that supports the understanding of concepts. General formal concepts exist precisely because there are a large number of real contexts in which they apply. However, developing a useful understanding of a formal concept relies on discovering it in several different real contexts. The variety of contexts bounds the concept establishing its characteristics, limits and conditions of use.

General remarks

Different representational frameworks are based on different conventions and underlying assumptions. By challenging one representation against another, a designer can uncover gaps in thought. The underlying assumptions of the different representational frameworks are often brought to the fore. For the engineering designer it seems to be particularly fruitful to challenge abstract against material representations. This process brings to light new information about hardware characteristics, the design requirements or the working explanatory model. In other disciplines it may make more sense to challenge one kind of abstract representation against another.

It is interesting to note that many successful theoreticians, notably Feynman and Tesla, mention in their autobiographies that they were childhood tinkerers. Other research work (Brereton 1998) has shown that successful students develop their understanding of unfamiliar fundamental physical concepts through habitually using them to try to explain the behaviour of physical devices. Once these fundamentals are well understood, these students can then extend their understanding to much more complex and abstract technical domains, with only the occasional need to re-represent and test ideas in the physical domain. They can also test ideas developed in one abstract representational framework through the use of a second abstract representational framework. However, one cannot develop a theoretical understanding of the physical world without these early experiences of constantly challenging abstract models against the physical world. This process ensures that assumptions, concepts and relations are encoded correctly by testing, correcting and verifying them in a variety of scenarios.

Conclusion

This chapter has presented a qualitative analysis of learning in design discussions, paying particular attention to how learning in design arises from negotiating between abstract and material representations. Abstract representations 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. The process of design always benefits from a variety of representations. Shifting between representations in order to understand how to close the gap between representations advances understanding of the design.

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Notes

1. Expressions that rely on their situation for significance are commonly called indexical, after the "indexes" of Charles Pierce (1933) (from Suchman, *Plans and Situated Actions*, p. 58).