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Understanding Behaviour from the Ground Up: constructing robots to reveal simple mechanisms underlying complex behaviour

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Students often have difficulty getting past the use of folk-psychological terms (e.g., *wants*, *loves*, *fears*) when explaining behaviour. They assume that complex behaviours require similarly complex causal structures. For this study, the authors developed a two-week robotics project to demonstrate that complex behaviours can also emerge from simple mechanisms. The project combined lectures, demonstrations of simple robots, and hands-on robot building and observing. Evaluations showed that students enjoyed the project, and essays revealed that they learned from the experience. The project accomplished four goals: (1) engaged students in generating and testing hypotheses, (2) demonstrated the power of a mechanistic approach, (3) showed how social behaviour can arise from simple behaviours of individuals, and (4) illustrated how natural selection operates at the level of the whole organism.

> A safe rule on encountering any abstract psychological noun is to make it concrete by changing it into the corresponding verb or adverb. Much difficulty and unnecessary controversy can thus be avoided. (Woodworth, 1940, p. 19)

Imagine two little creatures, bugs perhaps, that are attracted by a light source. When each is far from the source, they race toward the light. However, they differ considerably in their personalities. The first bug approaches the light straight on, slowing, coming to a rest and staying close to the light. The second bug exhibits more erratic behaviour, moving away and then back to the light. Sometimes, for no obvious reason, this second bug abandons the light for some distant glimmer. If these bugs were males and the lights were potential mates, one might characterize the two behaviour patterns as reflecting true love (or monogamy) versus promiscuity.

These words – *love*, *promiscuity* – are the kinds of words that people commonly use when trying to explain behaviour; however, love and promiscuity are not necessary elements for these action patterns. The two bugs and their behaviours are easily generated with components available at a hobby shop – light sensors that drive motors that drive wheels. They were drawn from Braitenberg's (1984) mini-classic, *Vehicles: Experiments in synthetic psychology*. The sensorimotor connections needed to create the two behavioural patterns are illustrated in Figure 1. Notice that 'love' and 'promiscuity' are not components of this mechanistic explanation.

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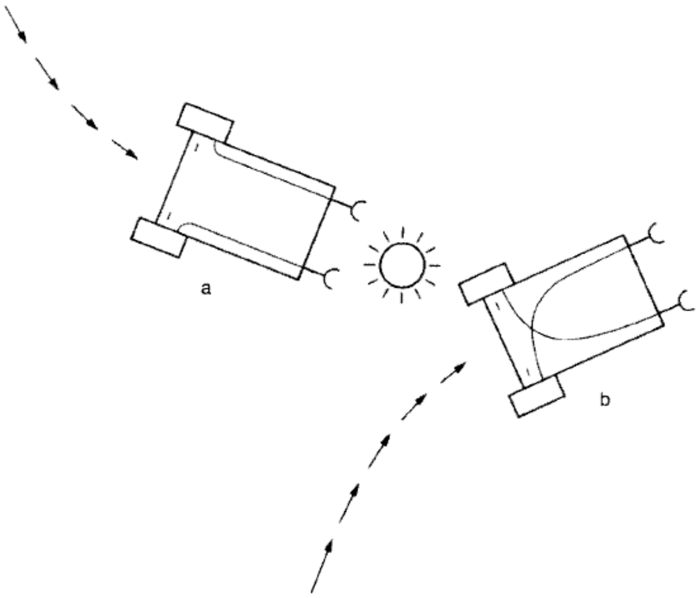
Figure 1. Mechanisms underlying 'true love' (vehicle A) and 'promiscuous' (vehicle B) behaviour. Both vehicles have spatially separated light sensors that drive wheels via negative (inhibitory) connections so that the stronger the light, the slower the approach. The vehicles differ only in whether the connections are straight or crossed. With straight connections, vehicle A orients to the light and moves in a straight course toward the source. Any deviation in course would slow the motor on the side nearest the light and correct the vehicle's path. Vehicle B, having crossed connections, moves in a fluttery pattern and always comes to rest facing away from the source. Thus vehicle B is easily snared by other lights. Given the light's inhibitory influence on speed of approach and the outward-facing light sensors, vehicle B often races off to distant lights. *Note.* From *Vehicles: Experiments in synthetic psychology* (p. 11), by V. Braitenberg, 1984, Cambridge, MA: MIT Press. Copyright 1984 by The Massachusetts Institute of Technology. Reprinted with permission.



Students have difficulty getting past such folk-psychological terms. Indeed, when asked to describe even the motions of simple geometric shapes, undergraduates assign human intentions to the shapes' actions (Heider & Simmel, 1944). This basic tendency to anthropomorphize, to assume intelligent and willful causal structures, presents a barrier to critical thinking about the mechanisms underlying observed behaviours. Scientific analyses of behaviour must discard these assumptions (Shettleworth, 2010; Wynne, 2004). If educators expect their students to adopt a scientific approach to psychology, and eventually to advance the field, we should motivate a healthy skepticism of anthropomorphisms, and an appreciation for how simple reflexive processes might give rise to complex patterns of behaviour.

We believe these bugs – or their hobby-shop incarnations – offer a way to help students get past folk-psychological anthropomorphic terms to underlying mechanisms. Building on Braitenberg (1984), we had students construct Lego robots that operated using only a few plain sensorimotor rules, but to the naïve observer, appeared to enact complex willful behaviour. Through hands-on activities with these robots, students would realize that complex actions can emerge from simple processes. Our teaching approach extends earlier experimental and theoretical classroom activities that use robots as demonstrative proofs of proposed mechanisms (Arkin, 1996; Miglino, Lund, & Cardaci, 1999; Pfeifer, 1996; Stewart & West, 2001; Sullivan, 2008).

We developed a two-week robotics project for an introductory psychology course to encourage students to think mechanistically about psychological phenomena and to provide concrete examples of how seemingly complex behaviours might emerge from simple mechanisms. Our project differed notably from previous approaches to robot-based learning activities, which either limited students to mere observation of prefabricated robots (e.g., Stewart & West, 2001), or sought to teach programming techniques and control architectures (e.g., Pfeifer, 1996). Instead our project balanced hands-on active learning with a degree of separation from the technical details of robot design, and moreover, we endeavored to empirically assess the impact of these activities on the way that students think about behaviour.

The project combined demonstrations, lectures, and hands-on building and observing experiences. Our teaching goals were to (1) immerse students in the self-correcting process of science by having them generate and test hypotheses, (2) demonstrate the power of a mechanistic approach in explaining complex behaviour, (3) show how social behaviour can arise from the simple behaviours of individuals, and (4) illustrate how natural selection operates at the level of the whole organism.

Method

Overview

The 16-week introductory psychology class had 25 students and was a 4-hour course (2 hours lecture, 2 hours lab weekly). We divided the 2-week robotics project into 2 sections, the first introducing the mechanistic approach and the second on mechanistic explanations of social behaviour and natural selection (Table 1). Before the project, the class had covered history of psychology and research methods. The project was followed by a section on neuroscience. Questions regarding the robot project were included in applicable quizzes and exams.

Table 1. Outline of robotics project.

	Day	Format	Goal	Activity
Week 1	1	1 hour lecture	Introduce mechanistic approach, contrast with folk-psychological approach.	Demonstrate simple autonomous robot, have class label behaviours and generate hypotheses.
	2	1 hour lecture	Explore possible mechanisms, both internal and external, that are responsible for the robot's behaviour.	Reveal the robot's simple pre-programmed rules, generate and test hypotheses about causes of robot's actions.
	3	2 hour lab	Show how behaviour is caused by activity at multiple levels of organisation, emphasising the role of the body as well as the brain.	Construct and test autonomous navigation ability of students' robots in walled arena.
Week 2	4	1 hour lecture	Demonstrate plausibility of mechanistic explanations for social behaviour.	Discuss requirements for robots to be sensitive to each other's behaviour, thus yielding group patterns of interaction.
	5	1 hour lecture	Illustrate utility of mechanistic approach in explaining real-world social behaviour.	Discuss robotic models of social behaviour in insects, birds, and rodents.
	6	2 hour lab	Show how natural selection modifies the population of robots.	Test students' robots in foraging survival competition.

The rights of students enrolled in this course were protected under an approved research protocol. Of the 25 students enrolled, 20 consented to our analysis of their work and sentiments about the course; responses of the 5 students who did not consent were not included in our analysis.

Apparatus

We used seven Lego Mindstorms Robotics Invention System kits (RCX version) to build our machines. Each kit contained touch and light sensors, motors, wiring, lots of Lego pieces, and a small on-board computer (which we refer to as the ‘brain’). Also included were illustrated guides for constructing and programming robots (see Appendix A for programming details). All pieces of the robot kits, including the wiring, could be connected in the familiar snap-together Lego style, so the students did not need specialized engineering skills. To keep the robots in a controlled, observable area during the robot demonstration and labs, we created a walled arena in the middle of the classroom.

Procedure

Days 1 and 2: Initial observations of robot behaviour. We began the first lecture with a live demonstration of SAM (Slightly Autonomous Machine), a small robot we built prior to class, with the capacity to seek out light sources while avoiding obstacles in its path (Figure 2). A floodlight provided a bright patch on the floor, and several boxes served as obstacles. As SAM meandered about the arena, the students (who had not been told anything about SAM’s programming) vocally labeled ‘what he was doing’. A list of behaviours was compiled on the chalkboard. Confirming our initial predictions, students ascribed intentions and goals to SAM’s behaviour, using terms such as ‘frustration’, ‘exploring’, ‘afraid’ (of the dark), ‘confused’, ‘liking’, and ‘happy’.

Figure 2. SAM (Slightly Autonomous Machine) served as a class demonstration robot. SAM’s antennae (wide horizontal bars) activated touch sensors, allowing the robot to avoid obstacles. SAM also carried a forward-facing light sensor just above the antennae. The large round ‘eyes’ at the top served no function other than to imply a more creature-like appearance. The robot was powered by two motors, each connected to a separate rear wheel.

After gathering and discussing these anthropomorphisms, on day 2 we revealed the three sensorimotor rules in SAM’s ‘head’, given in Appendix A. Once they learned of these simple perception/action reflexes, students discussed why they had given SAM so much psychological power, and during a guided lecture about Braitenberg’s *Vehicles* (1984), the class discussed the possibility that complex behaviours could emerge from simple mechanisms.

Day 3: Constructing robots and the power of a mechanistic approach. On the third day of the project, the students divided themselves into teams of four or five. We assigned each team a Mindstorms robot kit and instructed them to build a body capable of navigating an obstacle-filled classroom. Each of the supplied robot kits had identical ‘brains’ (all executing the same program described in Appendix A). Groups used about 45 minutes of class time to construct robots, using the Lego illustrated manuals as guides but ultimately creating radically different bodies (some with wheels, others with tank-like continuous tracks), each reflecting the creativity of the teams.

After some in-class time constructing their robots, the students' robots were tested in an obstacle-laden environment, with spotlights added to create patches of light. Students designated as 'observers' evaluated how long each robot could 'survive' before needing human assistance, and recorded frequency of assistance. Some robots appeared 'smart,' surviving for most of the trial, others 'dumb', requiring frequent assistance. They appeared to have different brains, but the smart ones differed from the dumb ones only in terms of their mode of locomotion and placement of their touch and light sensors. Students also measured amount of time spent in light versus dark areas. Differences in construction of the robots' bodies and positioning of the sensors created variation in patterns of interaction with the environment, and considerable differences in performance.

In open class discussion, students rapidly realized that these differences in their robots' behaviours could be explained without reference to folk-psychological terms. Indeed, the robots' behaviours could be accurately predicted only if those terms were discarded and replaced by a mechanistic framework.

Days 4 and 5: Simple mechanisms can build social behaviour. During the second week of the project, two lectures focused on mechanistic explanations of social behaviour. Group activity that seems complex and directed can be explained, like the behaviour of our robots, in terms of interactions between simple sensorimotor rules and a dynamic environment. As examples, we described rat pup (*Rattus norvegicus*) ambulatory and huddling behaviour (Alberts, 1978; Alberts, Motz, & Schank, 2003; Schank & Alberts, 1997) and the group antipredator response of Fall webworms (*Hyphantria cunea*) (Costa, 1997). The examples catalysed a lively student discussion of the possibilities of using autonomous robot animals to further investigate the origins of social behaviour. The students debated whether their Lego robots could produce patterns of group behaviour, and suggested combinations of sensorimotor rules and environmental conditions that would allow their robots to do so (for instance, adding light sources to the robots' 'bodies', or slowing motors when in contact with another robot). We guided this debate toward a discussion of how simple autonomous mechanisms might produce social behaviours that improve survival and reproductive fitness, and become heritable traits in the species.

Day 6: Natural selection acts on the entire organism. The second lab session demonstrated that evolutionary changes in behaviour act on the entire organism, not just the brain. If nature selects for behaviours that are embodied (determined by both brains and bodies), then selection must involve the behaviour of the whole creature, not the properties of some isolated cortical part.

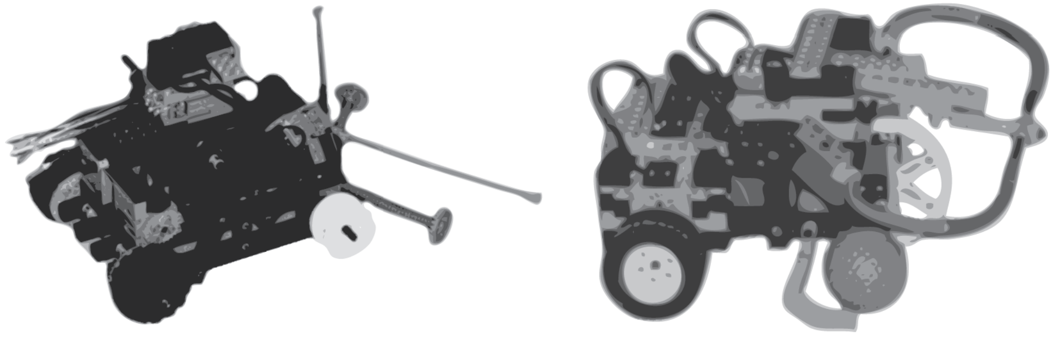
Teams were instructed to adapt their robots to compete in a ping pong ball 'foraging' contest, where balls were likened to robot food, and successful collection of balls was likened to survival and evolutionary fitness. We told the teams the scoring system for the foraging contest: a point would be awarded for each ball contacted, and an additional point could be gained for each second that the robot remained in contact with a ball. However, two points would be lost each time a robot became ensnared on an obstacle or other robot. Robots began a 10-minute trial with 10 points, and success was measured in terms of accumulated points at the end of the trial; running out of points meant death by starvation.

As before, all supplied 'brains' were identical. The teams had constructed these new creatures outside class (during the weekend between weeks 1 and 2), and again built very different robots; some had scoops or other devices for capturing balls while retaining separate bumpers or antennae for avoiding objects (see Figure 3).

The contest began with the balls randomly distributed across an empty arena floor, with a spotlight on one end. Faster robots were generally more successful, but the fastest robot, constructed with very large wheels, was a failure. Pure speed without appropriate visual and sensory apparatus (such as long 'feelers' for avoiding objects) doomed the robot. While cheering on their robots and tallying points, students learned that the fitness of a specific trait (e.g., sensorimotor connections or wheel size) could be accurately assessed only when the behaviour of the whole organism is observed.

We then shifted the environment and repeated the foraging contest. The robots had to forage for balls in an obstacle-filled environment, with heavy boxes added to the arena. Some of these boxes were wrapped in aluminum foil, to reflect light sources and complicate the robots' light-seeking behaviours. In this more complex environment, the slower and more maneuverable robots did better than the faster ones. Students learned that fitness depends not just on an organism's traits, but on the environment that it is in. In subsequent discussions, it became clear that minor changes to the robots' 'body' forms or to the robots' simple sensorimotor rules could have far-reaching impacts on complex behaviours, evolutionary fitness, and an organism's ability to survive in a specific ecological niche.

Figure 3. Examples of robots built by students. Each robot carried an identical program.



Evaluation and Discussion

Students' understanding of the concepts introduced in the robot project was recorded and assessed using quiz and exam prompts (given in Appendix B). One of these items ('Where does behaviour come from? Can we just study minds? Or do we have to study "minds in bodies"?') was asked twice; first in a quiz after the first week of the unit, and again in a quiz after the second week.

Additionally, on the last day of the semester, students filled out an evaluation of each major learning activity in the course, including the robot project (19 consenting students were present for this evaluation). The first three questions asked students to rate the projects on a 5-point scale for level of difficulty (1 = *unreasonable*, 5 = *too easy*), amount of work (1 = *unreasonable*, 5 = *too easy*), and amount learned (1 = *nothing*, 5 = *exceptional amount*). Two additional items were open-ended, asking students to describe the best and worst aspects of the robot project, specifically.

In their open-ended responses about the best and worst aspects of the project, students indicated that the robotics experience was unique, engaging, and interesting. Nearly every student noted that the project was fun, and many expressed gratitude for the opportunity to get to know their classmates in a creative way at the start of the semester, in the context of the competitive ping pong ball foraging contest. They also felt the project could be improved with more time to work with the robots, and some less technically inclined students expressed frustration at mechanical difficulties during the construction process.

Responses to the first two survey items, about workload and difficulty, are illustrated in Figure 4. Students indicated that the overall level of difficulty was moderate (M = 2.82, SD = 0.51) and the amount of work also moderate (M = 2.66, SD = 0.47), roughly comparable to conducting an original experiment. In contrast with other relatively easy active learning units implemented in this course (exploring taste illusions, and an overview of brain imaging technology), students found the robot project's workload to be balanced and appropriate.

In their response to the third survey item, students reported that they learned only a modest amount in the two-week unit (M = 3.28, SD = 0.67). While this is a positive rating, this value was significantly lower than the average ratings of the other units (M = 3.63, SD = 0.44), $t(17)$ = 2.36, p = .02 (two-tailed). On the surface, these ratings might suggest that the robot project was not an effective learning activity. However, our instructional goals for this robot unit were relatively subtle compared with other classroom projects, and student introspection about 'amount learned' is not the most accurate measure of whether our goals were met. Indeed, some of the most powerful educational experiences might be those where students are unaware that learning is taking place (Brown, Collins, & Duguid, 1989).

Figure 4. Student sentiment on workload and difficulty of robot project, compared with other projects.

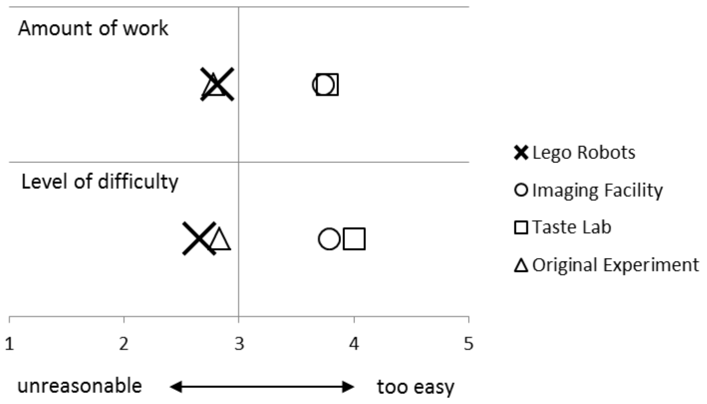


Table 2. Increasingly sophisticated student views on behaviour.

Responses to quiz question (asked twice): Where does behavior come from? Can we just study minds? Or do we have to study 'minds in bodies'? Explain your response.		Responses to essay exam question (See Appendix B)
After 1st week	After 2nd week	
Behavior comes from mental processes – including thoughts and feelings …	Even though all the robots had the same program, they did not behave the same ... This furthers the idea of studying 'minds in bodies' as we assess the psychological constructs through their behaviors ...	Behavior is not a product of the mind alone; the body/mechanisms and the environment contribute to the behavior that is observed ... In Braitenberg's vehicles, simple wiring changes caused different actions… Seemingly complex and intelligent behavior does not need central direction ...
Behavior comes from observable actions and some of the activities of cells within the brain, internal thoughts, and feelings …	If the mind was the single factor in determining behavior, all of the robots would have behaved in the same manner …	By examining the behavior of the various robots we built, we applied different anthropomorphisms such as timidity, curiosity, and stubbornness, even though the robots had no means by which to feel such things ... Though the underlying mechanisms are quite simple, it is common to view them with more complexity ...
Behavior comes from the goal oriented reaction to different stimuli ...	One must study minds in bodies because it is very easy to attribute human like characteristics to organisms. A particular reaction to a stimulus might be interpreted as intentional when in reality, such as in the robot's case, it is programmed ...	The emptying of a stadium seems immensely organized and complex when viewed on a large scale… The reality is that there are quite simple behaviors interacting to produce a more complex behavior... Vehicles and lego robots appear to 'like' or 'love' when it is just responding to stimuli ...

Note. These are relevant excerpts from representative quiz and essay responses from three students.

Rather than instilling them with new information, this project was intended to immerse students in a new way of thinking about complex behaviour, and refine their approach to the behavioural sciences. In spite of their moderate awareness of learning, the students demonstrated sharply increasing sophistication in their responses to quiz and exam questions. Statements such as 'He likes to hide behind boxes,' and 'He's surprised by the light', were typical during their first observations of SAM, but in subsequent written comments, students showed increasing scepticism and refinement of their original views (see Table 2). Those who were initially quick to apply human-like intentions to a robot began to see complex behaviours as emergent results of dynamic interactions between mind, body and environment. Moreover, in their exam responses, students showed that they could generalize their ideas from experiments with robots to the workings of nature and large-scale group interactions. Given the strength of the naïve tendency to view complex behaviours as designed and intentional, we feel that the robot project set a relevant and important benchmark for further study in psychology. Even though they might not have been explicitly aware of it, students learned to avoid imposing human-like wants and goals on organisms, to think critically about their own assumptions, and to place a premium on careful empirical observations of behaviour.

The robotics project teaches core concepts at the heart of experimental psychology and science. Moreover, these lessons are learned through 'hands-on' and fun experimentation with physical entities. This active-learning approach makes the mechanisms understandable, the rewards of experimentation (that is, correcting false beliefs) fast, and the joy and real-world value of science obvious. The project also propels students in one direction in which science and technology is surely heading. Seemingly willful and intelligent, autonomous creatures and devices are everywhere, and there is value in being able to think critically about their behaviours (Pfeifer, Lungarella, & Sporns, 2008). The lessons learned from working with the robots – distributed causality, emergent phenomena, mechanistic explanation, and the self-correcting nature of science – are useful lessons for everyone.

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APPENDIX A

We programmed SAM and the students' robots using the supplied RCX language, a simple graphical environment in which we dragged and dropped commands defining default behaviours and the relationships between sensory inputs and motor outputs. The program we created had three components: (1) A default 'searching' behaviour, moving forward for up to three seconds, and then gently turning for up to eight seconds; (2) an obstacle avoidance behaviour, triggered by one of two touch sensors, which immediately prompted backing and turning away from the obstacle for up to three seconds; and (3) an attraction to light, triggered by a forward-pointing light sensor, which initiated moving forward at full speed and playing a musical jingle until the light stimulus was no longer above the threshold. We found the programming easy to learn; an afternoon was all that was required to create the programs and build a simple robot as a test bed. See Baum (2000) or Boogaarts et al. (2007) for robot construction techniques and ideas.

APPENDIX B

Short answer questions for quizzes or journals:

1. What mechanisms might be responsible for SAM's behaviour? Can you think of possible different mechanisms?
2. What is the relationship between the goals, motives, and intentions we ascribe to organisms and the mechanisms that make behaviour?
3. Where does behaviour come from? Can we just study minds? Or do we have to study 'minds in bodies'? Explain your response.
4. How do multiple 'minds' create social behaviour? How can robot models help us better understand the emergence of social behaviour in living organisms?
5. What are the implications of embodied cognition for the evolution of behaviour? What gets acted on by selection? Rules in the head, physical structure, both, neither?
6. Vehicle 3 of the Braitenberg (1984) reading exhibits what might be described as 'love'. What does this (and the mechanisms of Braitenberg's other vehicles) suggest about the architecture underlying psychological constructs such as 'love'?

Essay exam question:

In a *New York Times* article ('In an online salon', 1997), Arthur De Vany wrote:

> A crowd can empty a large football stadium in minutes, solving what is an intractable computational problem and exhibiting large-scale intelligence in the absence of central direction. Why are decentralized processes ubiquitous throughout nature and society – evolution is itself such a process – and why do people remain so distrustful of them?

Discuss the relationship between this quotation, Braitenberg's vehicles, and the demonstrations in class.

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